POWER SYSTEM STABILITY ENHANCMENT USING UPFC DAMPING CONTROLLER

A Thesis submitted in partial fulfillment of the requirements for the degree of Master of Technology

In

Electrical Engineering

(Power Electronics and Drives)

By

Sudhansu Kumar Samal

Roll Number: 212EE4512

DEPARTM ENT OF ELECTRICAL ENGINEERING
NATIONAL INSTITUTE OF TECHNOLOGY,
ROURKELA ODISHA, INDIA
PIN-769008

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Under the Supervision of

Prof. Prafulla Chandra Panda

DEPARTM ENT OF ELECTRICAL ENGINEERING
NATIONAL INSTITUTE OF TECHNOLOGY,
ROURKELA ODISHA, INDIA
PIN-769008

(2012-2014)

Dedicated to

My beloved Parents

NATIONAL INSTITUTE OF TECHNOLOGY
ROURKELA

CERTIFICATE

This is to certify that the thesis report entitled "Power System Stability Enhancement Using UPFC Damping Controller" submitted by Mr. Sudhansu Kumar Samal in partial fulfillment of the requirements for the award of Master of Technology degree in Electrical Engineering with specialization in "Power Electronics and Drives" during session 2012-2014 at National Institute of Technology, Rourkela (Deemed University) and is an authentic work by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other university/institute for the award of any degree or diploma.

Prof. P. C. PANDA
Dept. of Electrical Engineering
NIT Rourkela

Date:
Place: Rourkela

ACKNOWLEDGEMENT

I would like to appearance my extreme gratitude to my supervisor Prof. P. C. Panda, Professor, Department of Electrical Engineering, NIT Rourkela. I feel encouraged and motivated every time I meet him. Without his inspiration and supervision, this project would not have materialized.

I am also thankful to Prof. A. K. Panda for his valuable suggestions towards the completion of my project. I would like to thank *Rakhi Panigrahi* and *Rajendra Prasad* and my friend *Saroj* and *Biranchi* for their help and moral support. Finally I would like to thank my *Parents* and elder *Sister Shantilata Samal* for their moral support and encouragement.

Apart after my hard work, the accomplishment of any project depends highly on the inspiration and guidance of several others. I yield this opportunity to express my gratitude to the people who have been instrumental in the successful achievement of this project.

The guidance and provision acknowledged from all the associates who help and who are backing to this project, was vital for the achievement of the project. I am very much obliged for their continuous support and assistance.

SUDHANSU KUMAR SAMAL

Roll No: 212EE4512

ABSTRACT

The rising of demand of power and difficulties of constructing a newly transmission network causes the power system to be complex and stressed. Due to the stress in the power system there is a chance of losing the stability following to the fault. When the fault occurs in the power system the whole system goes to severe transients. By using PSS and AVR we can easily stabilize the system. FACTS devices (i.e. TCSC, SVC, STATCOM, and UPFC) are extremely important to suppressing the power system oscillations for faults and it also increasing the damping of the system. The power electronic device named as UPFC which efficiently control the active and reactive power. This thesis reflects a novel control technique which is based on Fuzzy Logic technique to provide external controlling signal to UPFC which is mounted in a single-machine infinite bus system to suppress low frequency oscillations and also it describes the model of a UPFC with multi-machine system which is externally controlled by the signal which is generated by the newly proposed power flow controller to increase the stability of the system with occurrence of fault in which it connected. The proposed controller consists of Power oscillation damping controller and Proportional Integral Differential controller (POD & PID). The effectiveness of controller for suppressing oscillation due to change in mechanical input and excitation is examined by investigating their change in rotor angle and speed occurred in the SMIB system. FACTS devices are used the existing transmission system very efficiently with the specified stability margin.

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ABBREVIATION

FACTS	: Flexible AC Transmission Systems
TCSC	: Thyristor Controlled Series Capacitor
SSSC	: Static Synchronous Series Compensators
UPFC	: Unified Power Flow Controllers
PSS	: Power System Stabilizer
VSC	: Voltage Source Converter
LFO	: Low Frequency Oscillation
PFC	: Power Flow Controller
ANN	: Artificial Neural Network
POD	: Power Oscillation damping
S-L-G	: Single-Line-Ground
PID	: Proportional Integral Derivative
SVC	: Static VAR Compensator
STATCOM	: Static Synchronous Compensators

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INTRODUCTION

CHAPTER 1

1.1 Introduction – Now recent years, the power system design, high efficiency operation and reliability of the power systems have been considered more than before. Due to the growth in consuming electrical energy, the maximum capacity of the transmission lines should be increased. Therefore in a normal condition also the stability as well as the security is the major part of discussion. Several years the power system stabilizer act as a common control approach to damp the system oscillations [1-2]. However, in some operating conditions, the PSS may fail to stabilize the power system, especially in low frequency oscillations [3]. As a result, other alternatives have been suggested to stabilize the system accurately. It is proved that the FACTS devices are very much effective in power flow control as well as damping out the swing of the system during fault. Recent years lots of control devices are implemented under the FACTS technology. By implementing the FACTS devices gives the flexibility for voltage stability and regulation also the stability of the system by getting proper control signal [4].The FACTS devices are not a single but also collection of controllers which are efficiently not only work under the rated power, voltage, impedance, phase angle frequency but also under below the rated frequency. Among all FACTS devices the UPFC most popular controller due to its wide area control over power both active and reactive, it also gives the system to be used for its maximum thermal limit. It's primarily duty to control both the powers independently. It has been shown that all three parameters that can affect the real power and reactive power in the power system can be simultaneously and independently controlled just by changing the control schemes from one type to other in UPFC. Moreover, the UPFC is executed for voltage provision and transient stability improvement by suppressing the sub-synchronous resonance (SSR) or LFO [5]. For example, in it has been shown that the UPFC is capable of inter-area oscillation damping by means of straight controlling the UPFC's sending and receiving bus voltages. Therefore, the main aim of the UPFC is to control the active and reactive power flow through the transmission line with emulated reactance. It is widely accepted that the UPFC is not capable of damping the oscillations with its normal controller. As a result, the auxiliary damping controller should be supplemented to the normal control of UPFC in order to retrieve the oscillations and improve the system stability.

1.2 Power System Stability-The term stability exist due to the existence of the synchronous machine in the power system .The power which is available in the real world on the economical basis by the use of all conventional sources is all generated from synchronous generator. The generators are always located at the remote end of the load or distribution centers. And almost all or bulk quantity of power is generation is able to transmitted to the load center by using extra high voltage lines. Stability is the capability of the system to retain synchronism with externally connected transmission line by synchronous generator in order to deliver maximum power to either small, sudden load change. The two important parameters are usually defines the stability consideration are 1).supply frequency 2).The terminal voltage. In general the active or real power is only considered for the stability consideration, because any change in the load end is always reflects as a change in the rotor position of alternator. Most common word resembles in the stability are the acceleration and deceleration, moment of inertia, angular velocity, power angle etc. If we are talking about the stability it is nothing but a virtue of the system or some part of the system to develop a restoring force which is equal to the or greater than the disturbing force to maintain the stability or synchronism. The maximum power which can be transmitted through the system at any operating point is refer as a stability limit to the part of the system to which the stability limit refers is operating with stability. Generally for the analysis purpose we are considering three conditions.1).Steady State Stability 2).Transient Stability 3) Dynamic stability. [1] [6].

The ability to maintain synchronism by delivering maximum amount of real power for a small and gradual variation of load is simply termed as steady state stability. The rate of change of load is less than rate of change of excitation controller or the frequency of oscillation due to change of load are less than the natural frequency of the system.

If the system subject to the sudden and large variation of the load due to 3-phase short circuit fault occurred for only a time of 5 cycles, then the maximum amount of power that can be delivered to the load without losing the synchronism is called transient stability. If the oscillation persist after first swing of the rotor up to the point for which the rotor regain its new operating point to maintain the stability without losing the synchronism is called as dynamic stability.

1.3 Transient Stability- A synchronous power system seems transient stability if subsequently a huge, quick disturbance, it manages to recover and continue the state of synchronism. A quick huge disturbance comprises application of different faults, switching of the arrangement rudiments (loads, transmission lines, generators etc.).The study carried out for the transient stability is analyzed for short time that is equivalent to the first swing of the rotor. Normally the time period which we have considered is one second or less then of that. Because it seems that if the system being stable after a first swing then we can predict that the whole system remain stable and the proceeding swing diminish and all system are intact. [1] [7].

Assumption to evaluate the transient stability:

1. The resistance, the shunt capacitance of generator and the transmission lines are ignored. The shunt element like shunt capacitor (or) shunt inductor at load bus or generator bus are ignored. The network is represented as transfer reactance.
2. The input mechanical power is assumed to be constant.
3. The speed of the alternator remains constant.
4. The damping force provided by the damper winding assumed to be neglected.
5. The reactance voltage of the machine assumed to be neglected.

The transient stability can be analyzed by using the swing equation.

$$M\frac{d^2\,\delta}{dt^2} = P_s - \frac{E_v}{X}\mathrm{Sin}\delta$$

1.4 FACTS Devices-

1.4.1-FACTS System (FACTS): It defined as AC transmission network integrating semiconductor based power electronic device as well as different stationary controllers to increase the capacity of power flow and also expand the controllability of the system.

1.4.2-FACTS Controller: It includes power electronic devices as well as other static devices with advance power electronic conversion and switching capability.

It is significant to describe that some other static device which is used as a controller are not belongs to the power electronic family but basically the used controller are thyristor devices. When we are use the FACTS as a reactive power controller they are provided with minimum storage at dc side. The general symbol for FACTS Controller is shown in Fig. 1.2a. FACTS Controllers are distributed into four groups [8] [9].

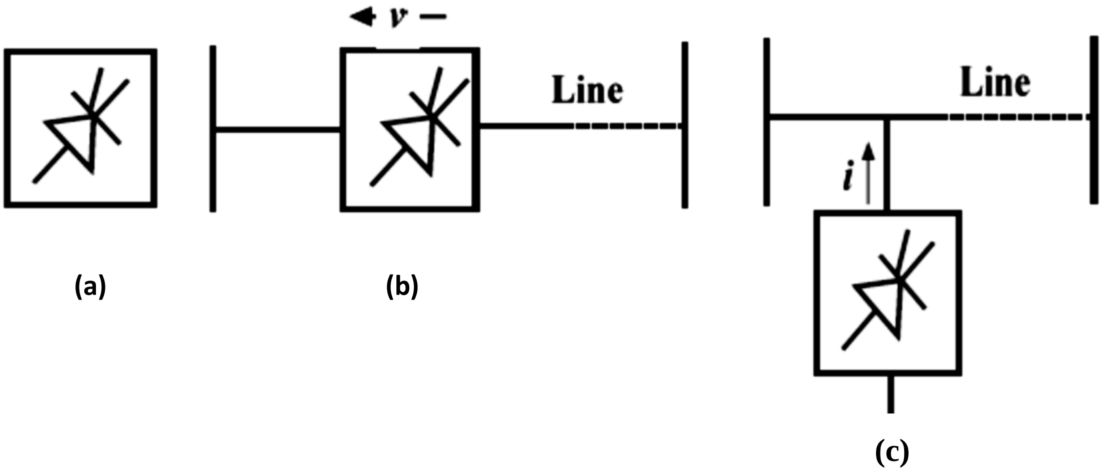
1] Series FACTS Controllers
2] Shunt FACTS Controllers
4] Combined Series-Shunt FACTS Controllers
3] Combined Series-Series FACTS Controllers

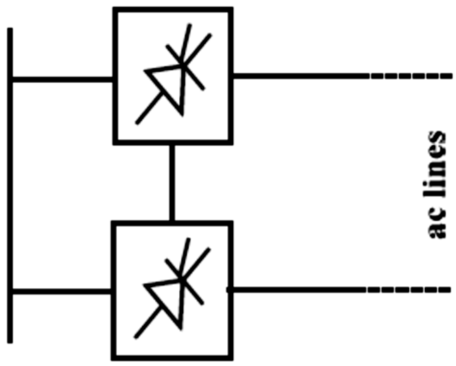
i) Series FACTS Controllers: - These FACTS Controllers are inject the voltage series through the connected line , if this series injected voltage is in phase quadrature to the line current, the controller simply deliver or receives the variable reactive power which is illustrated in Fig. 1.2b. Other than the quadrature with injected voltage and line current the controller can involve itself for real power control.

ii) Shunt FACTS Controllers: - The shunt FACTS Controllers have flexible impedance type i.e. reactor or capacitor adjustable source based on the power electronics , which is shunt connected to the line in order to inject variable current, as shown in Fig. 1.2c. Here up to which the current is injected to the line voltage with phase quadrature it deliveries or absorbs the reactive power to the system, other than that at any angle for voltage and current it well work for the real power flow.

iii) Combined Series-Series FACTS Controllers: -, as illustrated in Fig. 1.2d. This configuration provides autonomous series reactive power compensation for each line but also transfers real power among the lines via power link. The presence of power link between series controllers names this configuration as “Unified Series-Series Controller”.

iv) Combined Series-Shunt FACTS Controllers: - These are arrangement of distinct arrangement of series and shunt controller and they connected in such way that the control of both is much synchronized manner (Fig. 1.2e) or a UPFC connected with series and shunt controller (Fig. 1.2f). The real or active power exchange is take place through the power dc link when these controllers are connected to each other and also with the line.





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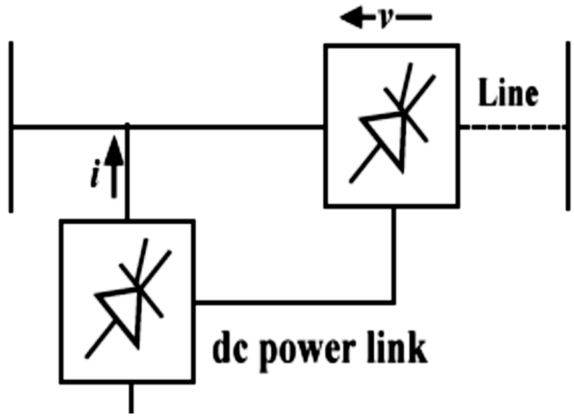

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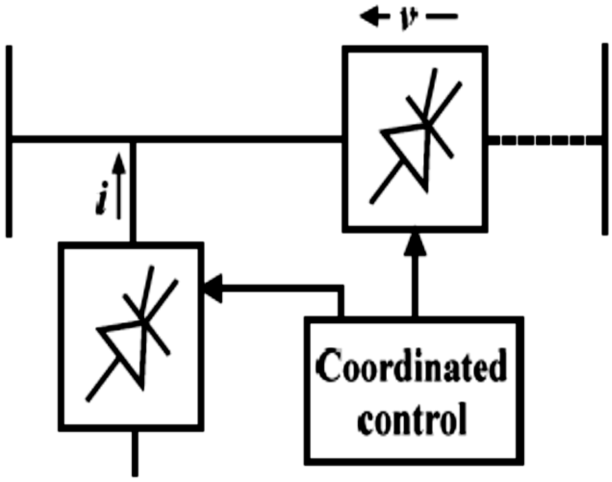


(f)

Fig.1.1 Schematic diagram of FACTS Devices (a) Representation for FACTS Controller, (b) Representation of Series FACTS Controller, (c) Symbolic representation of shunt FACTS Controller, (d) Schematic of a series-series FACTS Controller, (e) organized series and shunt Controller, (f) unified series-shunt Controller,

1.5 Literature Review - Power systems over the worldwide becoming complex day to day and continuous requirements are coming for stable, secured, controlled, economic and better quality power. These requirements become more essential when environment becoming more vital and important deregulation. Power transfer capacity in transmission system is limited due to various factors such as transient and steady state stability, thermal limit, damping of the connected system. The consequence of the degree of various parameters limit are given the electrical damping of power system require to be mitigate to steady oscillations allowed power transmission. FACTS System and Distributed Flexible AC Transmission System provides feasible and cost-effective solution to these problems and so these devices are required to use worldwide for improving performance of power system [8]. Thorough research works are going on in finding newer concepts for minimizing the reason of Voltage collapse. Minimizing reason of voltage collapse means increasing power system stability (Dynamic, transient and steady-state stability), voltage margin and voltage security in the system [5]. FACTS are basically designed to provide an alternate solution to meet the growing of power business and also it can transmit bulk power in the exiting transmission network. One of the measure tool to measure the dynamics of the system is the rate at which the transient energy will dissipated from the system, when the system is subjected to any type of fault basically short circuit fault there is a mismatch between the mechanical input and load and rotor speed deviation takes pace to achieve to stabilize the mismatch but sometimes it fails and system fall out of synchronism. To overcome that problem PSS are developed to measure the electromechanical transients. Location of the FACTS devices is a major area of research because to get better compensation we should have to be connected it at proper place, basically it is refers to be connected it at the middle of the system to get better result. The FACTS devices give better control to all the transmission parameter of the connected system in different manner [6]. One major aspect of stability to be discussed is the small signal stability of a SMIB system that named as Haffron-Philips model, when the system is subjected to the low frequency oscillations it refer as a small signal i.e. small incremental in load and if it persist for a long time then there may be provision of losing synchronism. UPFC connected with the SMIB system give good result on damping the low frequency oscillations, also it provide better idea about the effect of dc voltage regulator [11][12][13]. SMIB power system with Fuzzy-Logic based UPFC for controlling of LFO describes the effect of UPFC controller based on amplitude index of shunt converter (exciter) M_E been designed. Conventional Fuzzy-logic and Hybrid Fuzzy-logic with UPFC connected to the SMIB system gives better response to the low frequency oscillations [14].

1.6 Problem Formulation

Power system is more compound now days due to satisfy the emergent the request and superiority of power. Problem is raised when to fulfill this demand and quality restructuring of existing line required. Rearrangement of the line and increasing demand on the consumers end there is a huge burden on the connected system which is then leads to be stability as well as security problem for the whole existing system. It has been found that a quantity of black out have been caused by the lack of appropriate reactive power management which has to be mitigate also one important thing to be improve is the quality of power supplied to the distribution side.. The major problem now days are to mitigate the fault as soon as possible or the fault clearing time should be minutest. One other thing is also creating the stability problem is the frequent change in load demand and the excitation system.

1.7 Objectives and Scope of the Project

To study the steady state operating condition of the electrical network such as SMIB system with low frequency oscillations for sudden load change or excitation. The steady state may be determined by finding out the flow of active and reactive in the whole system with and without FACTS devices. To investigate the effect of FACTS devices (basically UPFC) for enhancing transient stability of the system to which it connected will be discussed. The simulation results of the SMIB system are performed at different fault conditions with different fault clearing time. Also interest is given to the finding the application of UPFC to damping the oscillation for both single and Multi machine power system in most possible fault clearing time.

1.8 Organization of the Thesis

Chapter 1

This chapter deliberates outline about FACTS and different FACTS Controllers, power system stability, and transient stability, and literature review, problem formulation, objective of the work and chapter wise contribution of the thesis.

Chapter 2

This chapter presents the Small signal analysis of SMIB, Modeling of Small Signal Stability of SMIB System (Heffron-Philips Model), Steady State and dynamic model of the UPFC, Power system stabilizer, conventional Fuzzy and Hybrid Fuzzy Logic Controller.

Chapter 3

This chapter presents the control concept of UPFC, UPFC based control system, Power system model with UPFC, Design of power flow controller (PID and POD),

Chapter 4

This chapter presents the Conclusion and Scope of future scope.

CHAPTER 2

MODELING OF UPFC FOR SMALL SIGNAL STABILITY ANALYSIS OF SMIB (HEFFRON-PHILIPS MODEL) SYSTEM.

CHAPTER 2

2.1 Introduction- This chapter investigates the small-signal stability of a SMIB system. It is seen that the SM connected to the infinite bus always concerned with the frequent load change and it may leads to be serious stability problem and should be discussed. Exploration of SMIB provides physical perception of the small but LFO. These oscillations are categorized by its nature of connection i.e. local mode; inter area mode and torsional mode. The SMIB system directly involve to the study of LFO [15].If proper damping is not supplied to the system then the small oscillation leads to create a savior instability problem. These chapters also investigate the impact of UPFC with SMIB system under low frequency oscillations by providing suitable damping signal using PSS. Fuzzy and Hybrid Fuzzy Logic Controller. By picking proper control parameter i.e. speed and angel deviation as a input function and using the knowledge base of the system performance with mamdani interface the Fuzzy logic generates the appropriate damping signal which can effectively reduce the system oscillation. And a compression study is made to see the effectiveness of these controllers [16] [17].

2.2 Small Signal Stability of SMIB System- A generator having induced emf E, d-axis transient reactance X_d' and terminal voltage V be associated with infinite bus (having voltage $|E_0|\angle 0^0$) over a line having reactance X_t. $|E_0|$ is constant although the operation while $|E|$ is constant during pre-disturbance Level [7].

Also $E = V^{(0)} + jX_d{}' I^{(0)}$ (1)

And $|X| = |X_d{}'| + |X_l|$ (2)

While $I = \dfrac{E\angle\delta - E_0\angle 0^0}{jX} \equiv \dfrac{E\angle 0^0 - E_0\angle -\delta}{jX}[with\ E\ as\, a\, reference]$

$$= \frac{E - E(\cos\delta - j\sin\delta)}{jX} \quad (3)$$

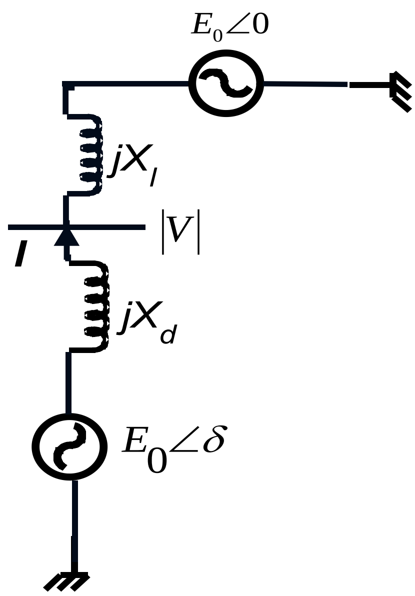


Fig 2.1 SMIB system

Where $V^{(0)}$ and $I^{(0)}$ are the pre-disturbance terminal voltage and current of generator, respectively. The generated complex power (or airgap power) at the infinite bus is obtented as

$$S_g = P_g + jQ_g = EI^* = \frac{|E||E_0|}{|X|}\sin\delta + j\frac{|E|(|E| - |E_0|\cos\delta)}{|X|} \qquad (4)$$

For the lossless generator, this air gap power or terminal power of generator

i.e. $$P_g = \frac{|E||E_0|}{|X|}\sin\delta \qquad (5)$$

In per unit, P_g (generated active power) is equal to the airgap torque.

i.e. $T_g = P_g$ (in per unit system)

$\therefore$ $$\Delta T_g = \frac{|E||E_0|}{|X|}\cos\delta_0 \cdot \Delta\delta \qquad (6)$$

Assume δ_0 as initial operating power angle.

The swing equation of the generator rotor is given by:

$$\frac{2Hd^2\delta}{\omega_0 dt^2} = P_m - P_e = T_m - T_e \qquad (7)$$

[In per unit $P_m = T_m$, while $P_e = T_e$, P_m be the mechanical power supply to the generator while P_e be the generated output.]

It is often required to add one component of the damping torque which is proportional to the speed deviation and swing equation is modified as follows:

$$\frac{2Hd^2\delta}{\omega_0 dt^2} = T_m - T_e - k_d \Delta\omega \tag{8}$$

Here, H =inertia constant,

ω_0 =synchronous speed,

T_e = Electrical torque (T_g), p.u.,

T_m = Mechanical torque, p.u.,

k_d =damping constant.

Let ω_r be the angular velocity of the rotor in rad/sec. If δ is the angular position of the rotor in electrical radian with respect to a synchronously rotating reference and δ_0 is the value at t=0, we have

$$\delta = (\omega_r t - \omega_0 t + \delta_0)$$

$$\frac{d\delta}{dt} = (\omega_r - \omega_0) = \Delta\omega_r \tag{8a}$$

$$\frac{d^2\delta}{dt^2} = \frac{d}{dt}\left[\frac{d\delta}{dt}\right] = \frac{d\Delta\omega_r}{dt}$$

To normalize the expression involving ω_r, let us rewrite, $\omega = \frac{\omega_r}{\omega_0}$ and then $\frac{d^2\delta}{dt^2} = \omega_0 \frac{d\Delta\omega}{dt}$

.thus in p.u., equation (8), we can be written as

$$2H\frac{d\Delta\omega}{dt} = T_m - T_e - k_d\Delta\omega \tag{8b}$$

Thus, we have two equations (8a) and (8b) expressing the dynamics of rotor. Let us represent these two equations as shown in (9a) and (9b).

From equation (8a), we can write:

$$\frac{d\delta}{dt} = \omega_0\Delta\omega \tag{9a}$$

And from equation (8b), we can write

$$\frac{d\Delta\omega}{dt} = \frac{1}{2H}(T_m - T_e - k_d\Delta\omega) \tag{9b}$$

From equation (9b) and (9a), we can write

$$p\Delta\omega = \frac{1}{2H}(T_m - T_e - k_d\Delta\omega) \quad (10a)$$

$$p\delta = \omega_0\Delta\omega \quad (10b)$$

And

It might be called the speed deviation in p.u., δ is the rotor angle (rad), and p is the differential operator $\frac{d}{dt}$.

Linearizing equation (10a) and using equation (6), we get

$$p\Delta\omega = \frac{1}{2H}(\Delta T_m - \Delta T_e - k_d\Delta\omega)$$

i.e. $$p\Delta\omega = \frac{1}{2H}(\Delta T_m - T_c\Delta\delta - k_d\Delta\omega) \quad (11)$$

Where T_c the synchronizing torque coefficient and is obtained from equation (6).

$$T_c = \frac{|E||E_0|}{|X|}\cos\delta_0 \quad (12)$$

Also, linearizing equation (10b), we get

$$p\Delta\delta = \omega_0\Delta\omega \quad (13)$$

Equations (11) and (13) can be written in a matrix from as

$$p\begin{bmatrix}\Delta\omega \\ \Delta\delta\end{bmatrix} = \begin{bmatrix}-\frac{k_d}{2H} & \frac{-T_c}{2H} \\ \omega_0 & 0\end{bmatrix}\begin{bmatrix}\Delta\omega \\ \Delta\delta\end{bmatrix} + \begin{bmatrix}\frac{1}{2H} \\ 0\end{bmatrix}\Delta T_m \quad (14a)$$

Or,

Where $\dot{x} = \frac{d}{dt}\begin{bmatrix}\Delta\omega \\ \Delta\delta\end{bmatrix}, A = \begin{bmatrix}-\frac{k_d}{2H} & \frac{-T_c}{2H} \\ \omega_0 & 0\end{bmatrix}, x = \begin{bmatrix}\Delta\omega \\ \Delta\delta\end{bmatrix}, b = \begin{bmatrix}\frac{1}{2H} \\ 0\end{bmatrix}, \ u = \Delta T_m$. (14b)

It may be observed that the element of state matrix A depends on k_d, H, X and the initial operating condition governed by E and δ_0.figure 2.2 represents the block diagram of the SMIB system.

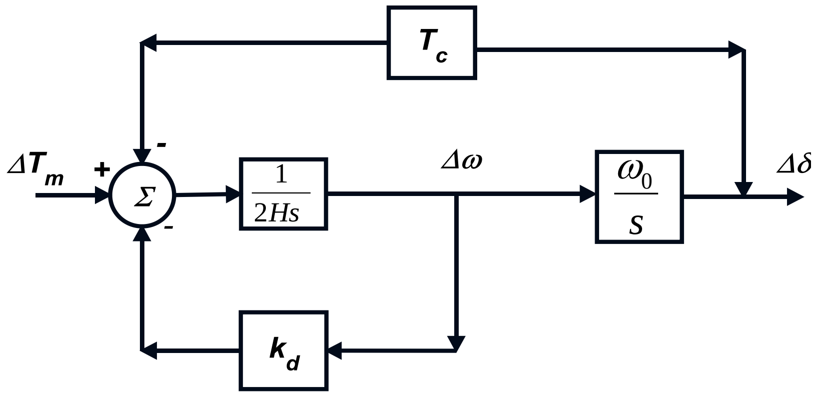


Fig.2.2 Block diagram representation of small signal SMIB model

From Fig. 2.2, we obtain

$$\Delta\delta = \frac{\omega_0}{s}\left[\frac{1}{2Hs}(-T_c\Delta\delta - k_d\Delta\omega + \Delta T_m)\right]$$

$$= \frac{\omega_0}{s}\left[\frac{1}{2Hs}(-T_c\Delta\delta - k_d s\frac{\Delta\delta}{\omega_0} + \Delta T_m)\right]$$

i.e. $$s^2(\Delta\delta) + \frac{k_d}{2H}s(\Delta\delta) + \frac{T_c}{2H}\omega_0(\Delta\delta) = \frac{\omega_0}{2H}\Delta T_m \tag{15}$$

The characteristic equation is then given by

$$s^2 + \frac{k_d}{2H}s + \frac{T_c}{2H}\omega_0 = 0 \tag{16}$$

[General form: $s^2 + 2\xi\omega_n s + \omega_n^2 = 0$]

The undamped natural frequency is then given as

$$\omega_n = \sqrt{T_c}\,\frac{\omega_0}{2H}\,rad/\sec \tag{17}$$

Damping ratio (ξ) is given by

$$\xi = \frac{1}{2}\frac{k_d}{2H\omega_n} = \frac{1}{2}\frac{k_d}{\sqrt{T_c 2H\omega_0}} \tag{18}$$

It may be observed that with increase in T_c, the synchronizing torque coefficient, the Natural frequency ω_0 increases while the damping ratio (ξ) decreases. If k_d is increased, the damping ratio (ξ) decreases .If k_d is increased, the damping ratio (ξ) increases. On the other hand, if H is increased, ω_n decreases along with reduction in damping ratio.

2.3 Modelling of Small Signal Stability of SMIB System (P-H Model) - SMIB model was mathematically analyzed in heffron-philips model and was used extensively by Demello and Cocordia for small signal analysis. In this model, a flux-decay system is linearized with Ed (d-axis induced emf of a generator) as an input and then a fast acting exciter is introduced. In the given state space model certain constant (*k_1 to k_6*) are identified: these constants are the function of operating condition. The state space model is then used to examine the eigenvalues as well as to design supplementary controllers to ensure adequate damping. The real and imaginary parts of the electromechanical model are associated with the damping and synchronizing torques [17] [18].

ω_0 =synchronous speed in rad/sec

ω =steady state angular speed of the alternator in rad/sec

δ =angle of induced voltage (v) in rad or degree

θ=angle of the terminal voltage of phase voltage at terminal in p.u.

V_d=direct axis component of the phase voltage at terminal in p.u

V_q=quadrature axis component of phase voltage at terminal in p.u

$V(= \sqrt{V_d^2 + V_q^2})$=terminal voltage per phase in p.u

$E_d^{'}$ =direct axis component of stator induced emf in p.u

$E_q^{'}$ =quadrature axis component of stator induced emf in p.u

$E^{'}[= \sqrt{E_d^{'2} + E_q^{'2}}]$=stator induced emf per phase in p.u

Id = direct axis component of armature current in p.u

Iq = quadrature axis component of armature current in p.u

E_{fd} = open circuit terminal voltage per phase in p.u

Xd = direct axis synchronous reactance in p.u

Xq= quadrature axis synchronous reactance in p.u

$X_d^{'}$ = direct axis transient reactance

$X_q^{'}$ = quadrature axis transient reactance in p.u

H= inertia constant in seconds.

Let us draw a simplified model of SMIB (Fig.2.3). We assume the machine is connected to the bus through an external impedance ($Z_l=R_l+jX_l$).

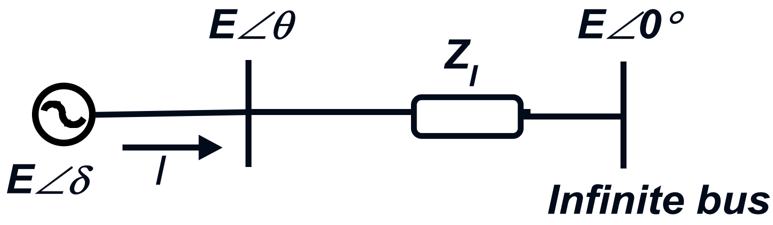


Fig.2.3 Simplified SMIB model for Heffron-Philips model.

The flux-decay model differential equation is as follows:

$$\frac{dE_q^{'}}{dt} = -\frac{1}{T^{'}_{do}}\left[E_q^{'} + (X_d - X_q^{'})I_d - E_{fd}\right] \tag{19}$$

$$\frac{d\delta}{dt} = \omega - \omega_0 \tag{20}$$

$$\frac{d\omega}{dt} = \frac{\omega}{2H}[T_m - \{E_q^{'}I_q + (X_d - X_d^{'})I_d I_q - k_d(\omega - \omega_0)\}] \tag{21}$$

The stator algebraic equations are

$$V\sin(\delta - \theta) + R_s I_d - X_q I_q = 0 \tag{22}$$

And $$E_q^{'} - V\cos(\delta - \theta) + R_s I_q - X_d^{'} I_d = 0 \tag{23}$$

In this model, we assume stator resistance R_s =0.The equation (22 and 23) thus can be represented as

$$X_q I_q - V\sin(\delta - \theta) = 0 \tag{22a}$$

$$E_q^{'} - V\cos(\delta - \theta) - X_d^{'} I_d = 0 \tag{23b}$$

Now $$\left(V_d + jV_q\right) \in^{j(\delta - \pi/2)} = V \in^{j\theta}$$

Hence, $$V_d + jV_q = V \in^{j\theta} \in^{-j(\delta - \pi/2)} \tag{24}$$

Expanding the RHS of the equation (24), we have

$$V_d + jV_q = V\sin(\delta - \theta) + jV\cos(\delta - \theta) \tag{25}$$

Equating the real and imaginary parts,

$$V_d = V\sin(\delta - \theta); V_q = V\cos(\delta - \theta)$$

Substitution of V_d and V_q in (22a) and (23b) yields

$$X_q I_q - V_d = 0 \tag{26}$$

$$E_q^{'} - V_q - X_d^{'} I_d = 0 \tag{27}$$

Cross multiplication and separation into real and imaginary parts yield

$$R_l I_d - X_l I_q = V_d - E_0 \sin\delta \tag{29}$$

$$X_l I_d - R_l I_q = V_q - E_0 \cos\delta \tag{30}$$

Hence ,for a SMIB model, the differential equations are given by equations(19-21) while algebraic equations are obtained as shown in equations (26),(27),(29) and(30).The next to linearize these equations around variables like I_d, I_q, θ, V_d and V_q.

Solving for ΔI_d and ΔI_q, we get

$$\begin{bmatrix} \Delta I_d \\ \Delta I_q \end{bmatrix} = \frac{1}{\Delta}\begin{bmatrix} \left(X_l + X_q\right) & -R_l E_0 \cos\delta_0 + \left(X_l + X_q\right)E_0 \sin\delta_0 \\ R_l & R_l E_0 \sin\delta_0 + (X_d^{'} + X_l)E_0 \cos\delta_0 \end{bmatrix} \times \begin{bmatrix} \Delta E_q^{'} \\ \Delta\delta \end{bmatrix} \tag{31}$$

Linearizing the three differential equations (19-21) and substituting the values of I_d, and I_q, we find the following equations:

$$\begin{bmatrix} \Delta\dot{E}_q^{'} \\ \Delta\dot{\delta} \\ \Delta\dot{\omega} \end{bmatrix} = \begin{bmatrix} -\frac{1}{T_{do}^{'}} & 0 & 0 \\ 0 & 0 & 1 \\ -\frac{\omega_0}{2H} I_{q0} & 0 & \frac{-\omega_0}{2H} k_d \end{bmatrix} \begin{bmatrix} \Delta E_q^{'} \\ \Delta\delta \\ \Delta\omega \end{bmatrix} + \begin{bmatrix} -\frac{1}{T_{d0}^{''}}(X_d - X_d^{'}) & 0 \\ 0 & 0 \\ \frac{\omega_0}{2H} I_{q0}(X_d^{'} - X_q) & \frac{\omega_0}{2H}(X_d^{'} - X_q)I_{d0} - \frac{\omega_0}{2H}E_{q0}^{'} \end{bmatrix} \begin{bmatrix} \Delta I_d \\ \Delta I_q \end{bmatrix} \tag{32}$$

$$+\begin{bmatrix} -\frac{1}{T_{do}^{'}} & 0 \\ 0 & 0 \\ 0 & +\frac{\omega_0}{2H} \end{bmatrix} \begin{bmatrix} \Delta E_{fd} \\ \Delta T_m \end{bmatrix}$$

Substituting for ΔI_d and ΔI_q for equation (32), we get

$$\left.\begin{aligned} \Delta\dot{E}_q^{'} &= -\frac{1}{k_3 T_{do}^{'}}\Delta E_q^{'} - \frac{k_4}{T_{do}^{'}}\Delta\delta + \frac{1}{T_{do}^{'}}\Delta E_{fd} \\ \Delta\dot{\delta} &= \Delta\omega \\ \Delta\dot{\omega} &= -\frac{\omega_0 k_2}{2H}\Delta E_q^{'} - \frac{\omega_0 k_1}{2H}\Delta\delta - \frac{k_d \omega_0}{2H}\Delta\omega + \frac{\omega_0}{2H}\Delta T_m \end{aligned}\right\} \tag{33}$$

The parameters (k_1 to k_6) all changes with operating condition, except k_3 (which is ratio of impedance). These equations represent the linearized minor perturbation relation of a sole generator connected with an Infinite bus through external impedance. Suffix 0 stands for initial value. The linearized P-H model is shown in the Fig.2.4.

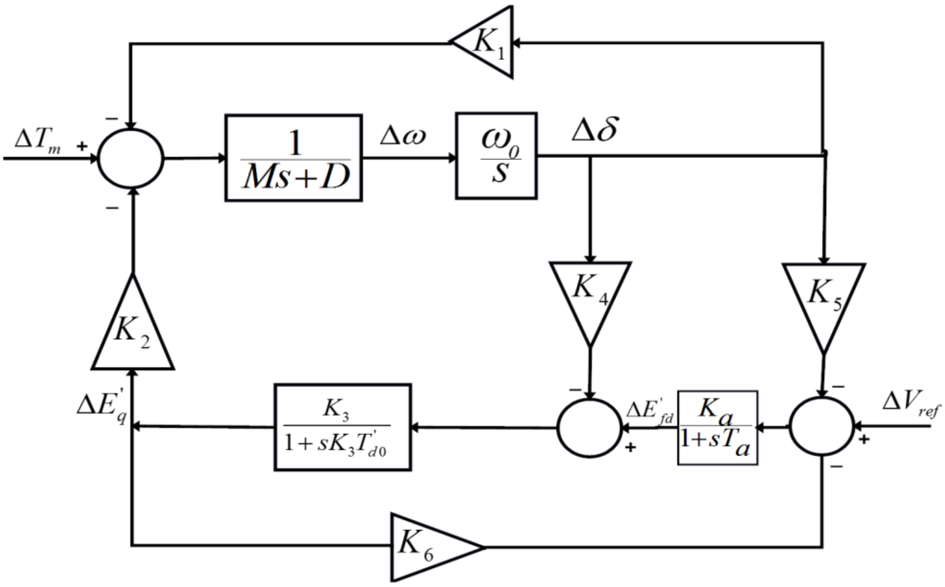


Fig.2.4 The linearized Phillips-Heffron model

2.4 Steady-State Model of the UPFC- In the fig 2.5 it shown that the bus "i" and bus "j" act as a sending end and receiving end bus and the UPFC is installed between then, with its steady state representation we assumed that the impedances of both series and shunt branches of UPFC are pure reactance. If we are considering the steady state operation of the system then the real power injected by the voltage source is zero and the between two voltage source the real power exchange will take place. Fig.2.6 shown the three power injection model converted from two voltage source. We can remove the shunt reactance from the system admittance

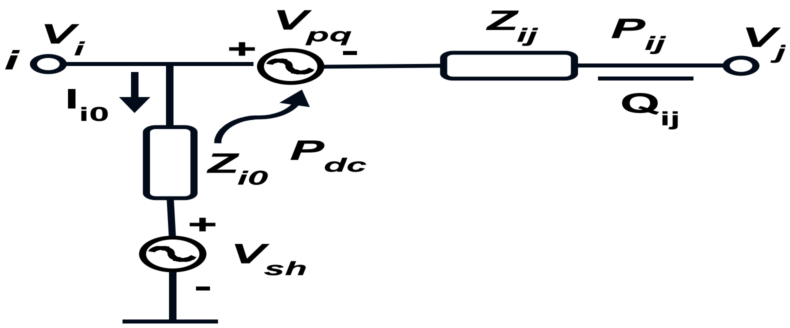


Fig.2.5. A UPFC with two-voltage source

matrix because we considered it as an injected reactive power i.e. "Q_{ij}". Here P_{io}, Q_{io} are real and reactive power represents the shunt voltage source and P_i, P_j, and Q_i, Q_j are the real and reactive powers represent the series voltage source. For load flow analysis we consider this two buses as a load buses and the power injected to the buses as follows:

$$\left.\begin{aligned}
P_{i0} &= \frac{|V_i||V_{sh}|}{x_{i0}}\sin(\delta_i-\delta_{sh}) \\
Q_{i0} &= \frac{|V_i|^2}{x_{i0}}-\frac{|V_i||V_{sh}|}{x_{i0}}\cos(\delta_i-\delta_{sh}) \\
P_i &= -\frac{|V_i||V_{pq}|}{x_{ij}}\sin(\delta_i-\delta_{pq}), Q_i=\frac{|V_i||V_{pq}|}{x_{ij}}\cos(\delta_i-\delta_{pq}) \\
P_j &= \frac{|V_j||V_{pq}|}{x_{ij}}\sin(\delta_j-\delta_{pq}), Q_j=-\frac{|V_i||V_{pq}|}{x_{ij}}\cos(\delta_i-\delta_{pq})
\end{aligned}\right\} \quad (34)$$

The operation with UPFC is done by neglecting the losses during the operation. The above statement resembles that the dc link voltage remains continual at the pre-defined value V_{dc}.

$$\mathrm{Re}\{V_{sh}I_{sh}^{*}+V_{pq}I_{pq}^{*}\}=0 \quad (35)$$

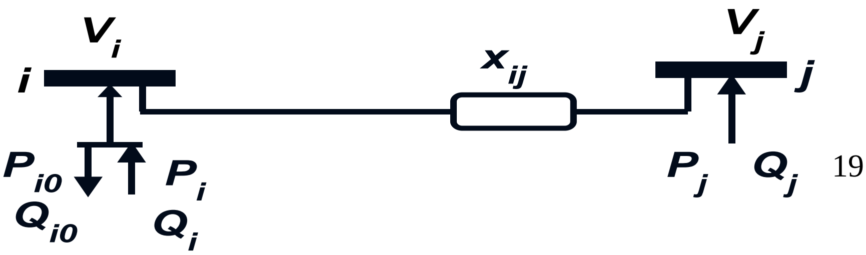


Fig.2.6. UPFC injected voltage model

By using Eqn. (34) the Eqn. (35) may be exemplified for its power constraint and the mathematically is satisfied for the operation for UPFC at steady-state.

$$\delta_{sh}=\delta_i-\sin^{-1}\left\{\frac{|V_{pq}||x_{ij}|}{|V_{sh}||V_i|x_{i0}}\Big[|V_i|\sin(\delta_{pq}-\delta_i)-|V_j|\sin(\delta_{pq}-\delta_j)\Big]\right\} \quad (36)$$

2.5 Dynamic Model of the UPFC- Figure.2.7 shows a SMIB power system connected to UPFC, where the control signals m_E, m_B and δ_E, δ_B are the amplitude modulation ratio and phase angle of the both VSC. This control signals treated as a input to the UPFC. Here we have considered two models for our study one linearized power system model for small signal stability and one dynamic model of UPFC to investigate effect over the system oscillation. Here we have to assume the transient effect and the resistance of the transformers of UPFC are zero for stability study [11] [18]. The dynamic equations of UPFC written as follows:

$$\left.\begin{aligned}
\begin{bmatrix} v_{Etd} \\ v_{Etq} \end{bmatrix} &= \begin{pmatrix} 0 & -X_E \\ X_E & 0 \end{pmatrix} \begin{bmatrix} i_{Ed} \\ i_{Eq} \end{bmatrix} + \begin{bmatrix} \dfrac{m_E v_{dc} \cos(\delta_E)}{2} \\ \dfrac{m_E v_{dc} \sin(\delta_E)}{2} \end{bmatrix} \\
\begin{bmatrix} v_{Btd} \\ v_{Btq} \end{bmatrix} &= \begin{pmatrix} 0 & -X_B \\ X_B & 0 \end{pmatrix} \begin{bmatrix} i_{Bd} \\ i_{Bq} \end{bmatrix} + \begin{bmatrix} \dfrac{m_B v_{dc} \cos(\delta_B)}{2} \\ \dfrac{m_B v_{dc} \sin(\delta_B)}{2} \end{bmatrix}
\end{aligned}\right\} \tag{37}$$

$$\frac{dv_{dc}}{dt} = \frac{3m_E}{4C_{dc}} [\cos(\delta_E)\ \ \sin(\delta_E)] \begin{bmatrix} i_{Ed} \\ i_{Eq} \end{bmatrix} + \frac{3m_B}{4C_{dc}} [\cos(\delta_B)\ \ \sin(\delta_B)] \begin{bmatrix} i_{Bd} \\ i_{Bq} \end{bmatrix}$$

By combining equation (37) and machine dynamic equation of the UPFC, we can develop complete dynamic model of the SMIB system connected with UPFC as follows:

$$\begin{aligned}
&E'_q = (-E_q + E_{qe}) / T'_{d0}, E'_{qe} = K_A (V_{to} - V_t) / (1 + sT_A) \\
&\dot{\delta} = \omega_0 \Delta\omega, \Delta\dot{\omega} = (P_m - P_e - D\Delta\omega) / 2H
\end{aligned} \tag{38}$$

By merging and linearizing Equations (37) and (38), the power system with UPFC state equations as follows:

$$\begin{bmatrix} \Delta\dot{\delta} \\ \Delta\dot{\omega} \\ \Delta E'_q \\ \Delta E'_{qe} \end{bmatrix} = \begin{bmatrix} 0 & \omega_0 & 0 & 0 \\ -\dfrac{K_1}{M} & -\dfrac{D}{M} & -\dfrac{K_2}{M} & 0 \\ -\dfrac{K_4}{T'_{d0}} & 0 & \dfrac{K_3}{T'_{do}} & \dfrac{1}{T'_{do}} \\ -\dfrac{K_A K_s}{T_A} & 0 & -\dfrac{K_A K_6}{T_A} & -\dfrac{1}{T_A} \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta\omega \\ \Delta E_q \\ \Delta E_{qe} \end{bmatrix} + \begin{bmatrix} 0 \\ -\dfrac{K_{pd}}{M} \\ -\dfrac{K_{qd}}{T'_{do}} \\ -\dfrac{K_A K_{vd}}{T_A} \end{bmatrix} \Delta V_{dc}$$

$$+ \begin{bmatrix} 0 & 0 & 0 & 0 \\ -\dfrac{K_{pe}}{M} & -\dfrac{K_{p\delta e}}{M} & -\dfrac{K_{pb}}{M} & -\dfrac{K_{p\delta b}}{M} \\ -\dfrac{K_{qe}}{T'_{d0}} & -\dfrac{K_{q\delta e}}{T'_{d0}} & -\dfrac{K_{qb}}{T'_{d0}} & -\dfrac{K_{q\delta b}}{T'_{d0}} \\ -\dfrac{K_A K_{ve}}{T_A} & -\dfrac{K_A K_{v\delta e}}{T_A} & -\dfrac{K_A K_{vb}}{T_A} & -\dfrac{K_A K_{v\delta b}}{T_A} \end{bmatrix} \begin{bmatrix} \Delta m_E \\ \Delta\delta_E \\ \Delta m_B \\ \Delta\delta_B \end{bmatrix} \tag{39}$$

Where Δm_E , Δm_B , $\Delta\delta_E$ and $\Delta\delta_B$ be the deviance of control input signals of the UPFC

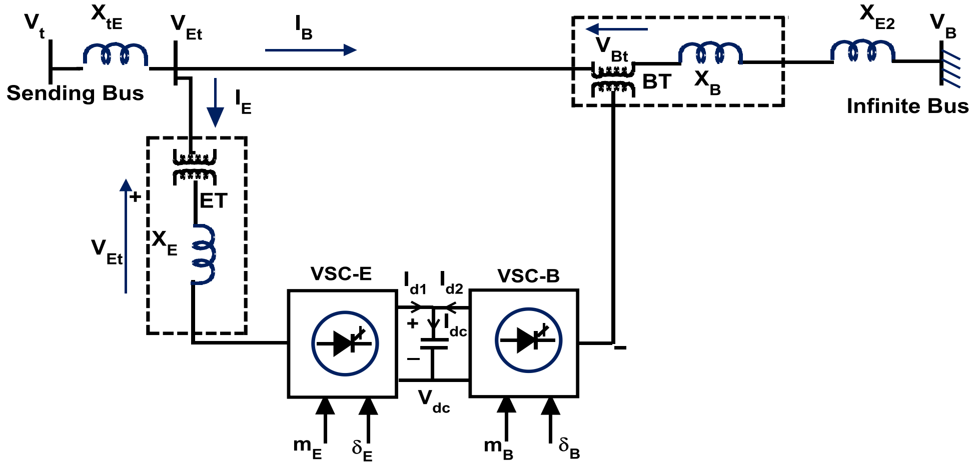


Fig.2.7. A UPFC installed in SMIB system.

This linearize model (Figure 2.8.), which is then established by increasing the nonlinear differential equations about a normal operational point. Here the performance of the SMIB system has been studied under different disturbances i.e. frequent load changes, the constants of the UPFC are calculated as:

$$
\begin{aligned}
\Delta f &= \begin{bmatrix} \Delta v_{dc} & \Delta m_E & \Delta\delta_E & \Delta m_{B\Delta} & \Delta\delta_B \end{bmatrix} \\
K_p &= \begin{bmatrix} \dfrac{K_{pd}}{M} & \dfrac{K_{pe}}{M} & \dfrac{K_{p\delta e}}{M} & \dfrac{K_{pb}}{M} & \dfrac{K_{p\delta b}}{M} \end{bmatrix} \\
K_q &= \begin{bmatrix} \dfrac{K_{qd}}{T'_{do}} & \dfrac{K_{qe}}{T'_{do}} & \dfrac{K_{q\delta e}}{T'_{do}} & \dfrac{K_{qb}}{T'_{do}} & \dfrac{K_{q\delta b}}{T'_{do}} \end{bmatrix}^T \\
K_v &= \begin{bmatrix} \dfrac{K_A K_{vd}}{T_A} & \dfrac{K_A K_{ve}}{T_A} & \dfrac{K_A K_{v\delta e}}{T_A} & \dfrac{K_A K_{vb}}{T_A} & \dfrac{K_A K_{v\delta b}}{T_A} \end{bmatrix}^T
\end{aligned} \tag{40}
$$

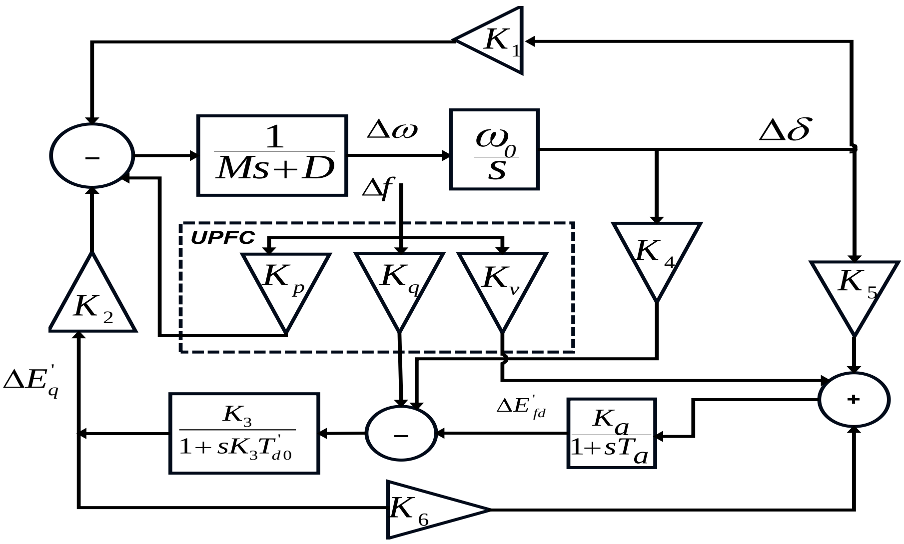


Fig.2.8. H-P model of SMIB system with UPFC

2.6 Power System Stabilizer-An economic and satisfactory solution to the unstable oscillations a power system produces is to provide additional damping (to rotor windings) for the generator rotor. This is done via Conventional PSS which gives additional controllers to the excitation system [7]. The input Vs to the exciter (Figure 2) is, as seen in Figure 2.9 the output from the Power System Stabilizer whose input signal originates from rotor velocity (or frequency). Conventional Power System Stabilizers are modeled in the following manner: The Power System Stabilizer implemented consists, as shown in Figure 2.9, of three main functional blocks:

- **The Washout gain**
- **The Washout Circuit**
- **The Lead-Lag Compensator**

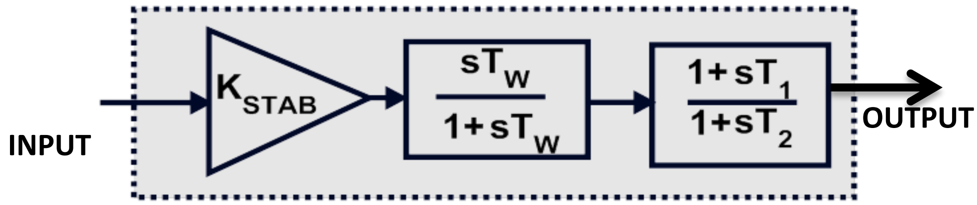


Fig 2.9. Conventional PSS

The Gain of PSS:

The Gain is simply the proportional gain of the PSS.

The Washout Circuit:

At the output of the PSS there is a steady state bias which modifies the generator terminal voltage; this is eliminated through the use of a Washout Circuit [5]. In the input signal the Power System Stabilizer acts upon only the transient variations. It doesn't however take any action when DC offsets in the signal are present. By subtracting the low frequency components from the input signal (through the use of a low-pass filter essentially) the DC offset present in the signal can be removed. Hence it can be said that Washout Circuits are essentially High-Pass filters which pass all frequencies that are of interest. It is understood that the system under investigation is of local mode nature and so the Tw value be placed in the range of 1 and 2.

The Dynamic Compensator, Lead – Lag Compensation:

The final process contained within the Power System Stabilizer is the Dynamic Compensator. This stage comprises of lead-lag stages and has the transfer function as shown in Figure 6.

The Lead-Lag stage utilizes the rotor shaft angular velocity and uses it as the inputs signal (as mentioned previously about the Washout Circuit) [7]. The Lead-Lag time constants: T1 and T2 were allocated values such that when the PSS is included in the feedback loop the overall closed loop of the H-P model and UPFC is stable at a set operating point. See Figure 2.10.

Tuning:

Given the above knowledge of PSS, the following values for the various parameters in relation to it were allocated

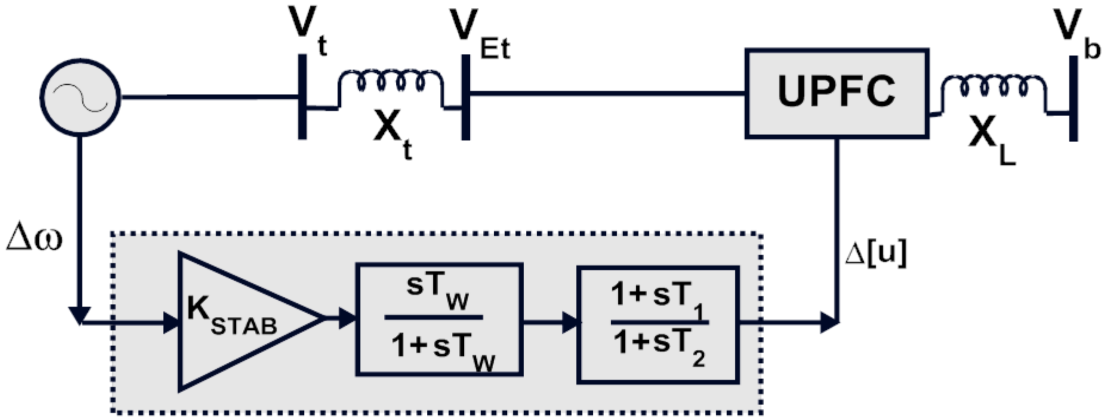


Fig. 2.10 UPFC with Power System Stabilizer

2.7 Fuzzy Logic Controller-

In order to providing stabilizer signal, the output of obtained model reference of power system is compared with output of real power system and the error signal is fed to a fuzzy controller [14]. The Fuzzy controller provides stabilizer signal in order to damping system oscillations. Fig. 2.11. Present the block diagram of proposed Fuzzy logic controller. In fact Fuzzy logic controller is one of the most effective operations of fuzzy set theory; its key features are the use of linguistic variables relatively than numerical variables. This control technique depends on human competency to understand the system performance and is based on quality control rules. Fuzzy logic provides a simple technique to reach at a definite conclusion created upon ambiguous, uncertain, inaccurate, noisy, or lost input information. FLC work on the principle of simple understanding of the system behavior of a person and simple rule based *"If x and y then z",* this rule base again defined by some membership function of FLC with proper argument to enhance the system performance [16] [17] [18]. The UPFC with Fuzzy controller is shown in the figure 2.12. Inaccurate, noisy, or lost input information. FLC work on the principle of simple understanding of the system behavior of a person and simple rule based *"If x and y then z",* this rule base again defined by some membership function of FLC with proper argument to enhance the system performance [16] [17] [18]. The UPFC with Fuzzy controller is shown in the figure 2.12.

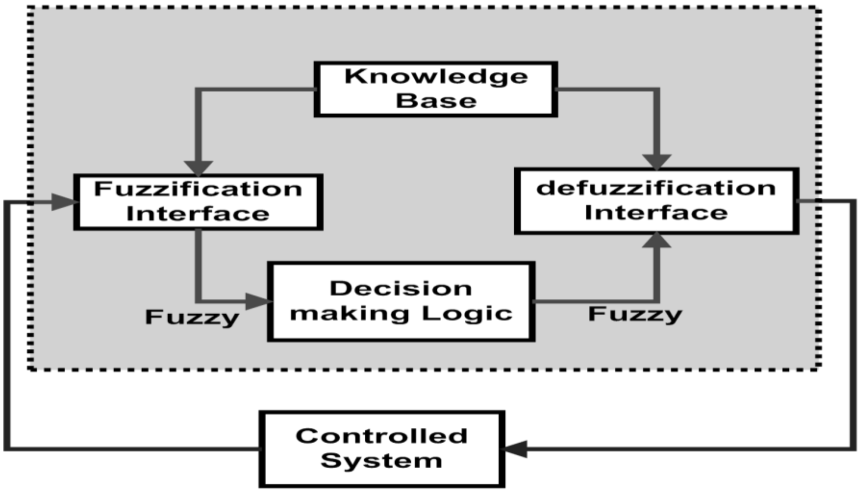


Fig. 2.11 Basic structure of Fuzzy Controller

- A Fuzzyfication is a prosses or platform in which we can convert the input data into linguistic variable.
- A Knowledge Base which contains the data base with the required linguistic definitions and control rule set.
- A Defuzzyfication interface which yields a non-fuzzy control action after an incidental fuzzy control action.
- A Decision Making Logic creates a platform where fuzzy logic action from the knowledge base with the linguistic variable and human decision process get to gather to give the appropriate decision.

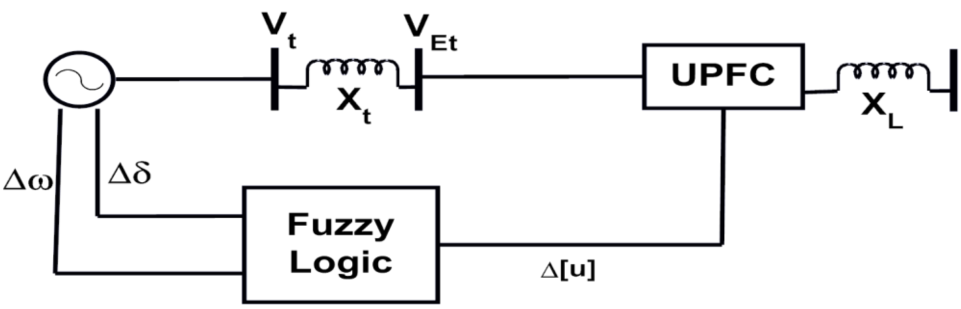
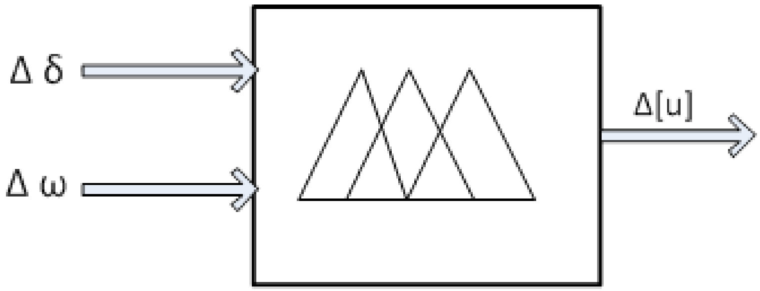


Fig.2.12 UPFC with FLC

FLC parameters: -

FLC structure:



The Rules used in this controller are chosen as follows:

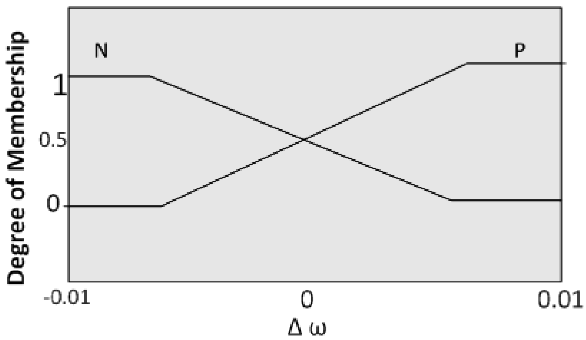
If Δω is P and Δδ is P then Δ[u] is P.

If Δω is P and Δδ is N then Δ[u] is Z.

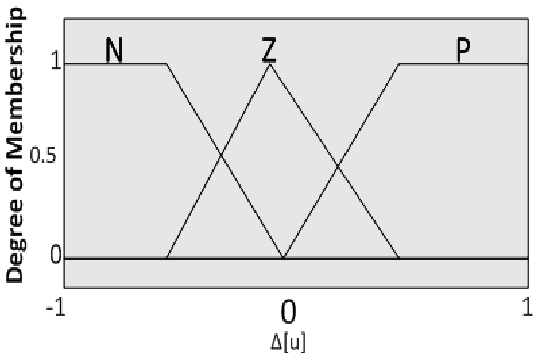
If Δω is N and Δδ is P then Δ[u] is Z.

If Δω is N and Δδ is N then Δ[u] is N.

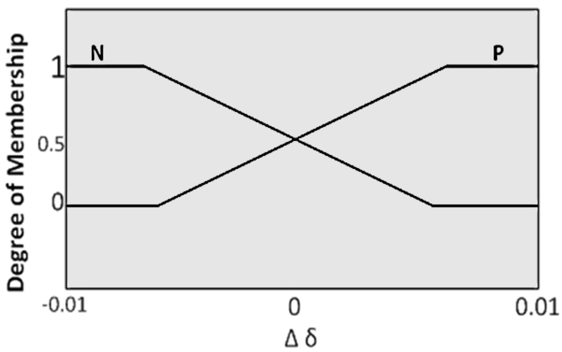
Input and output membership functions:



Input Membership Function



Ouput Membership Function



Input Membership Function

2.7.1 Hybrid Fuzzy Logic Controller-It is a combination of conventional FLC and conventional PI controller. The internal arrangement of the hybrid fuzzy damping controller displayed in the Fig.2.13.The membership functions, the rule base used here is same as of conventional FLC.

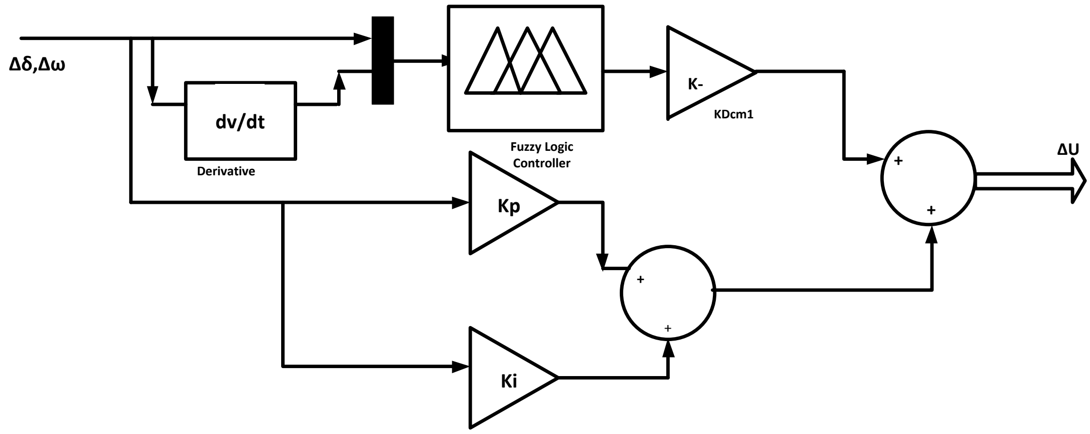


Fig. 2.13 Hybrid fuzzy damping controller structure

2.8 SIMULATION RESULTS and DISCUSSION

The ***K-constants*** *of SMIB system are calculated under the nominal condition with and without UPFC*:

$$K_1 = 1.1253, K_2 = 0.29611, K_3 = 0.46154, K_4 = 0.20755, K_5 = -0.01055, K_6 = 0.49647$$

$$K_{pe} = 0.53564, K_{qe} = 2.1595, K_{ve} = 0.49398$$

Operating condition:

$V_t = 1.0\,p.u, V_b = 1.0\,p.u, f = 50Hz$

Parameter of DC link capacitor:

$V_{dc} = 2, C_{dc} = 1$

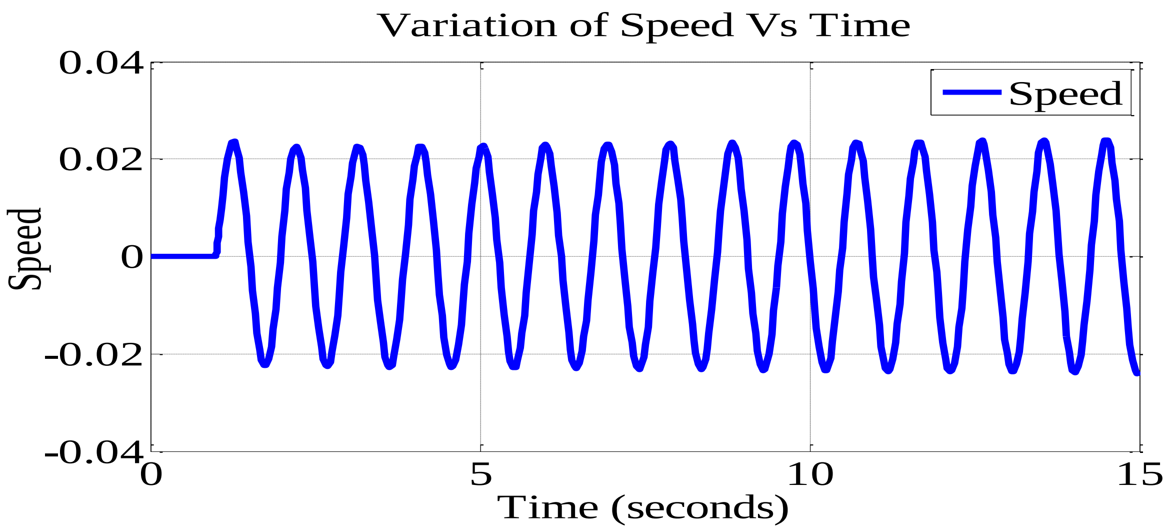
Constants for PSS Controller [17]:
$K_{STAB} = 4.33, T_w = 2, T_1 = 0.45012, T_2 = 0.1133, \max = 0.15, \min = -0.015$

Excitation System:
$T_A = 0.05, K_A = 50$
Power System Data:
$T'_{d0} = 7.76, X_d = 1.0, X_q = 0.6, X'_d = 0.3, H = 4, M = 2H$.
Hybrid Fuzzy Logic Data [19]:
Kp=5, K_i=5, K_D=1

The output of the simulation model is taken as speed deviation (Δω) angle deviation (Δδ). So, the following response is performed for speed deviation (Δω) and angle deviation (Δδ) against time from simulation model using SMIB system. The simulation process is carries for duration of 10 seconds [11].

SIMULATION RESULTS:

- Effect Step change in mechanical Power input on Power System Oscillations without UPFC. From viewing response of the system in figure 2.14 we have, the variation in speed and angle is oscillatory in nature. Due to formation of these oscillations the system is unstable. To improve the system performance and getting the stable position we have to eliminate these oscillations. To eliminate these oscillations we install UPFC with this SMIB system.



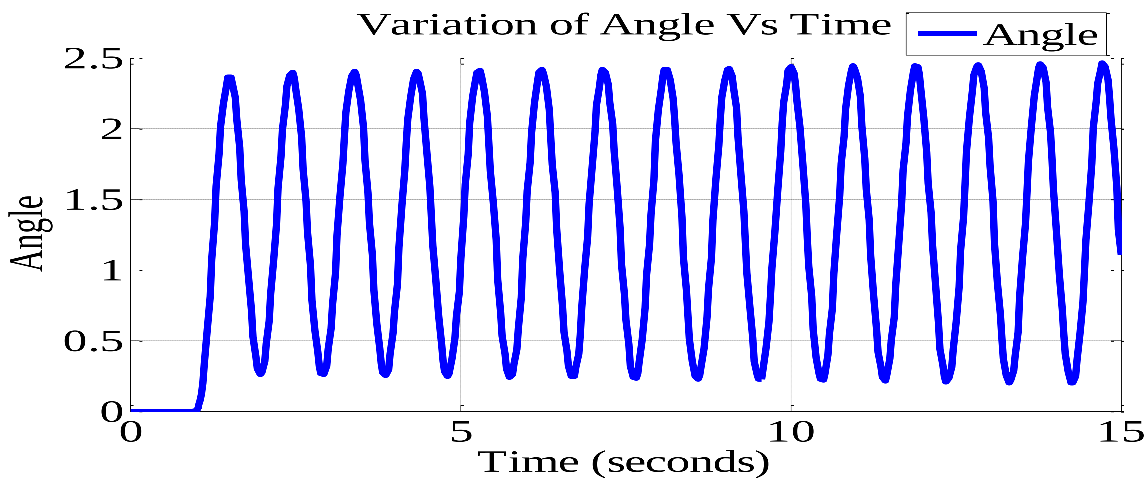


Fig. 2.14 Response of SMIB system without UPFC

- Effect Step change in mechanical Power input on Power System Oscillations with UPFC without external controlling signal is shown in the Figure 2.15. By calculating constants for FACTS device (UPFC) *i.e. Kp, Kq and* K_v. We can see the effect of

UPFC on power system. As we know that, the significant control parameters of UPFC are m_E, m_B and δ_B δ_E. By controlling these parameters we can control the magnitude of voltage through reactive power compensation at a bus where the UPFC is installed, also we can control the magnitude of the series injected voltage. Also we can regulate the d.c link voltage.

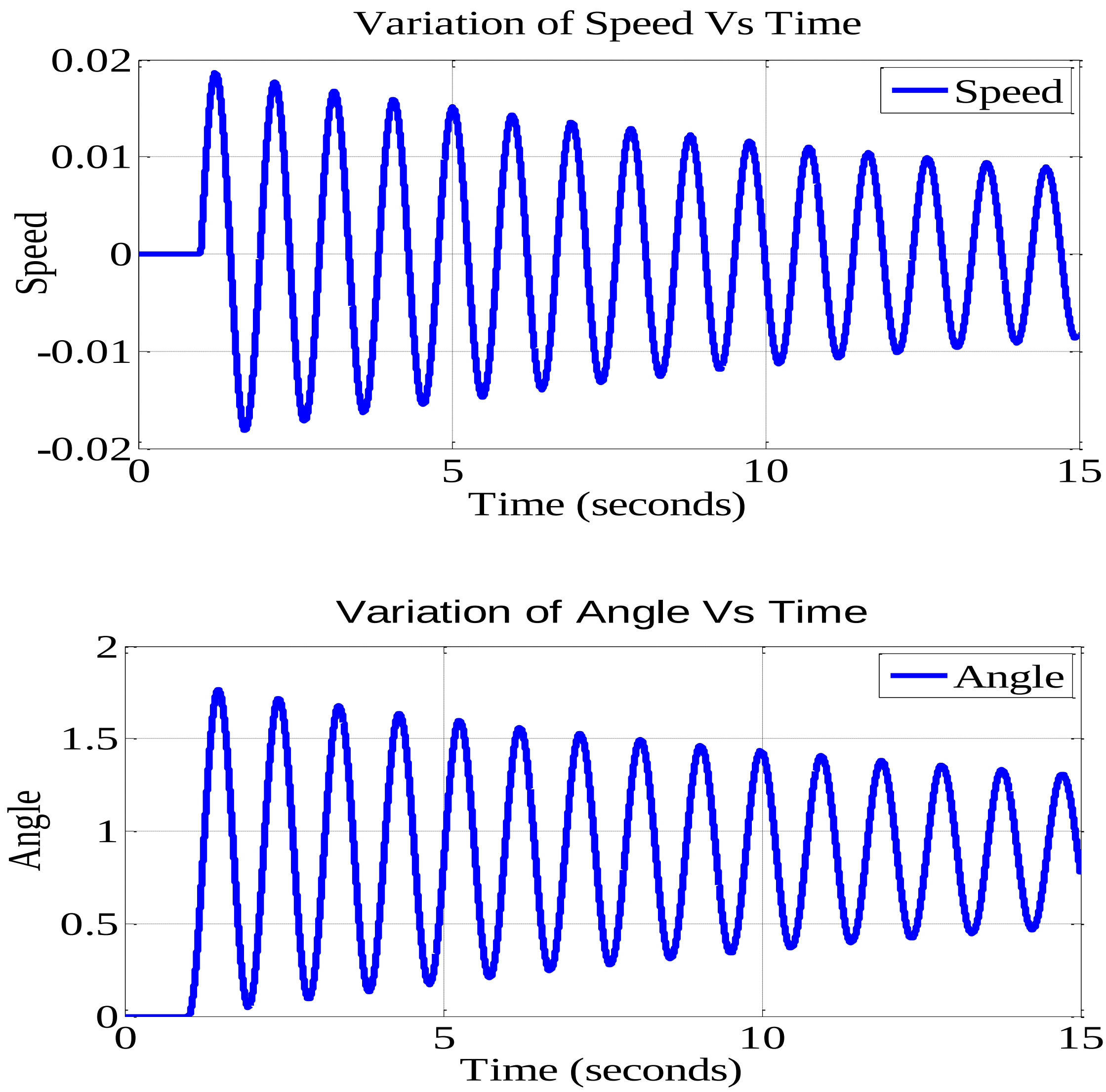


Fig. 2.15 Response of SMIB system with UPFC

- Effect Step change in mechanical Power input on Power System Oscillations with UPFC and external controlling signal from power system stabilizer is shown in the Figure 2.16. As we can see that using UPFC the oscillation of SMIB is reduced. But still the system is having oscillations which should be damped. So we install a damping controller on UPFC.

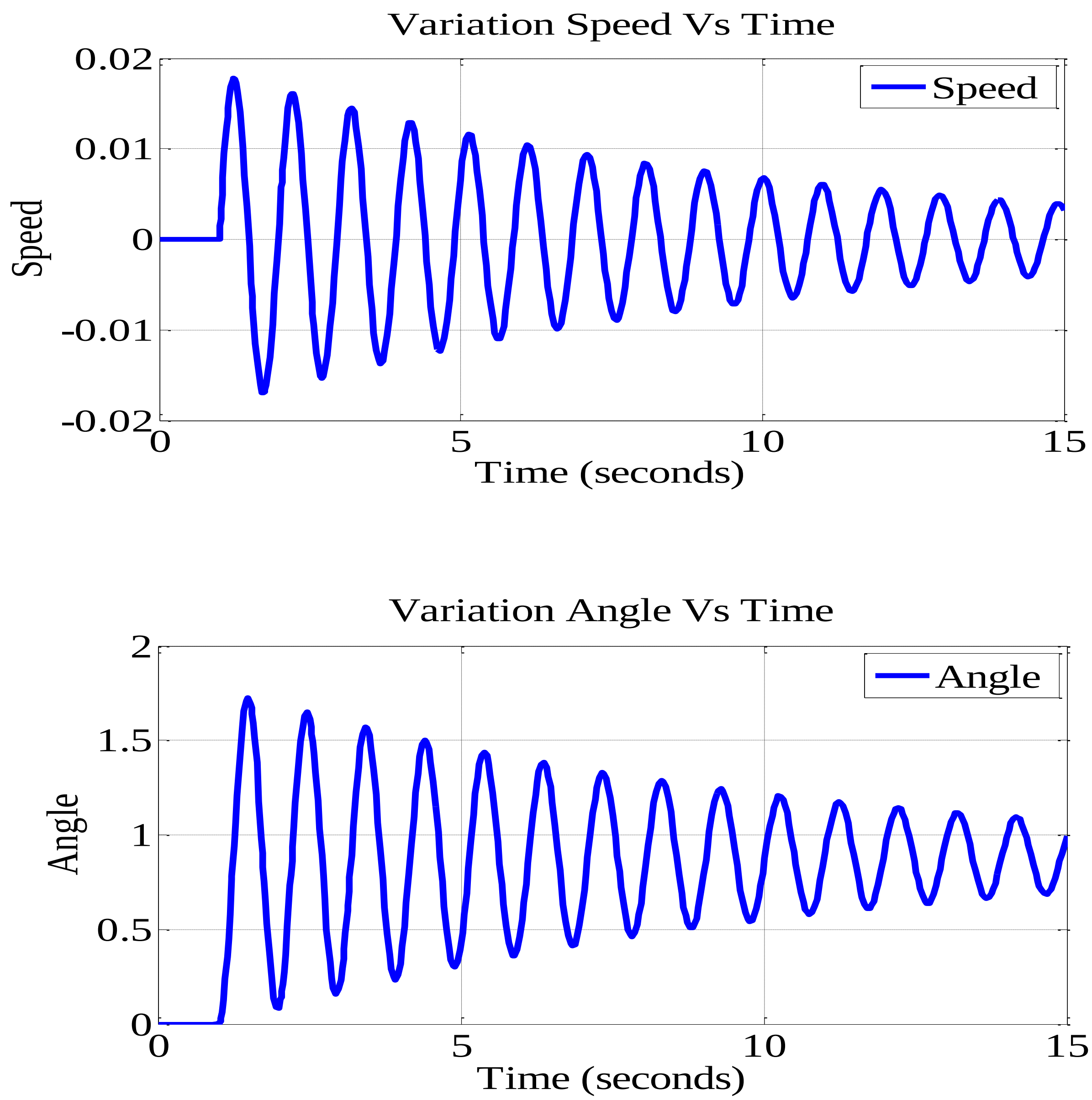


Fig. 2.16 Response of SMIB system with UPFC and Power System Stabilizer

- Effect in mechanical power input to the excitation on System Oscillations with UPFC and external controlling signal from Conventional -FLC is shown in the Figure 2.17. In this sub section we install a fuzzy damping controller for UPFC.

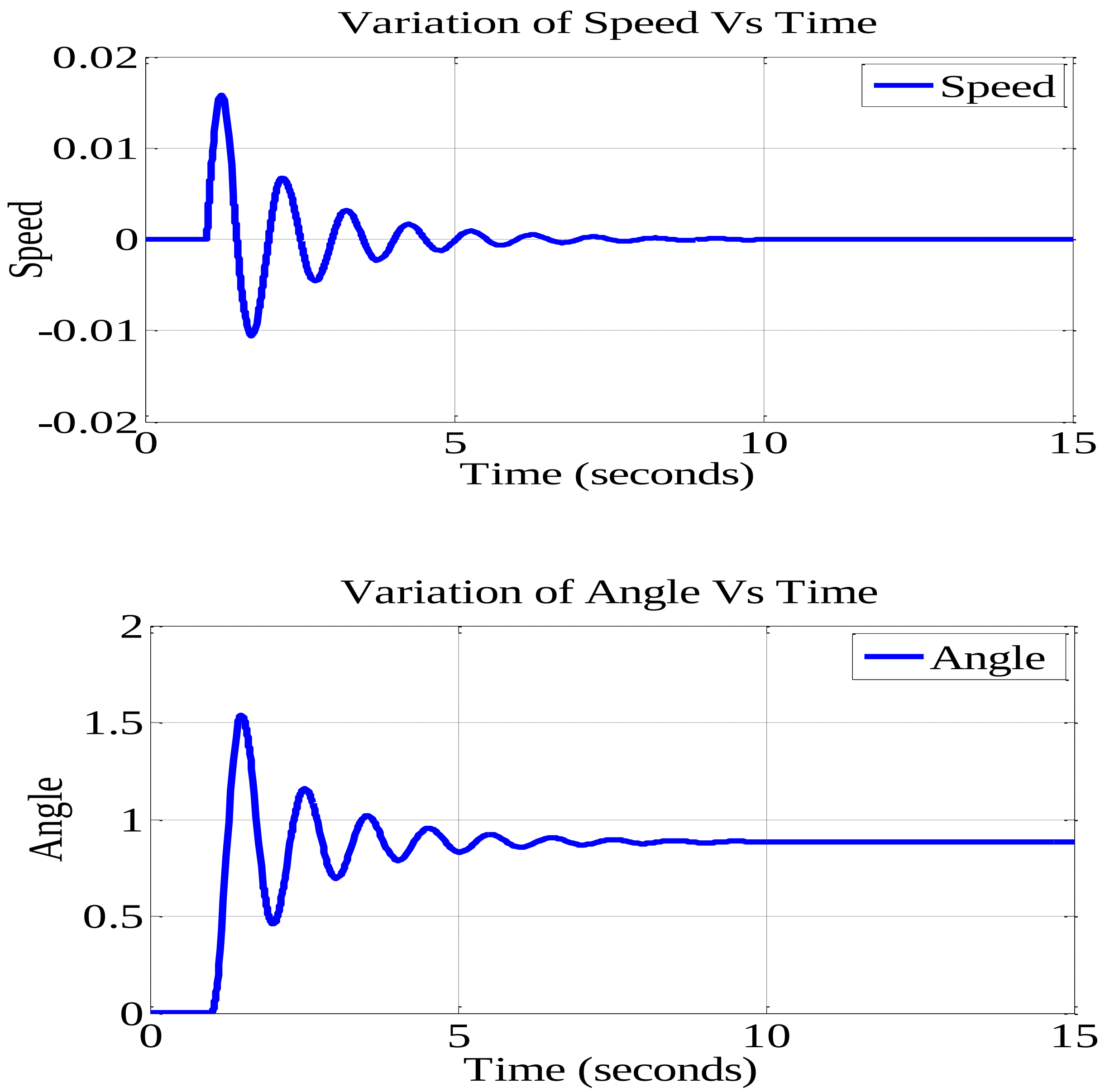
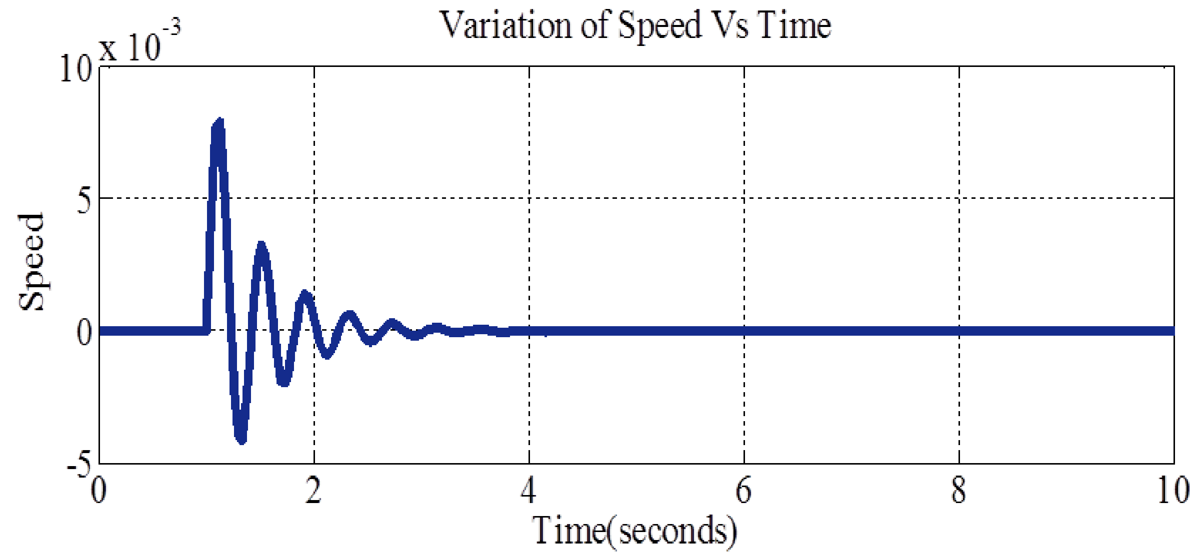


Fig. 2.17 Response of SMIB system with UPFC and Conventional Fuzzy Logic Controller

- Effect in mechanical power input to the excitation on System Oscillations with UPFC and external controlling signal from Hybrid -FLC is shown in the Figure 2.18.



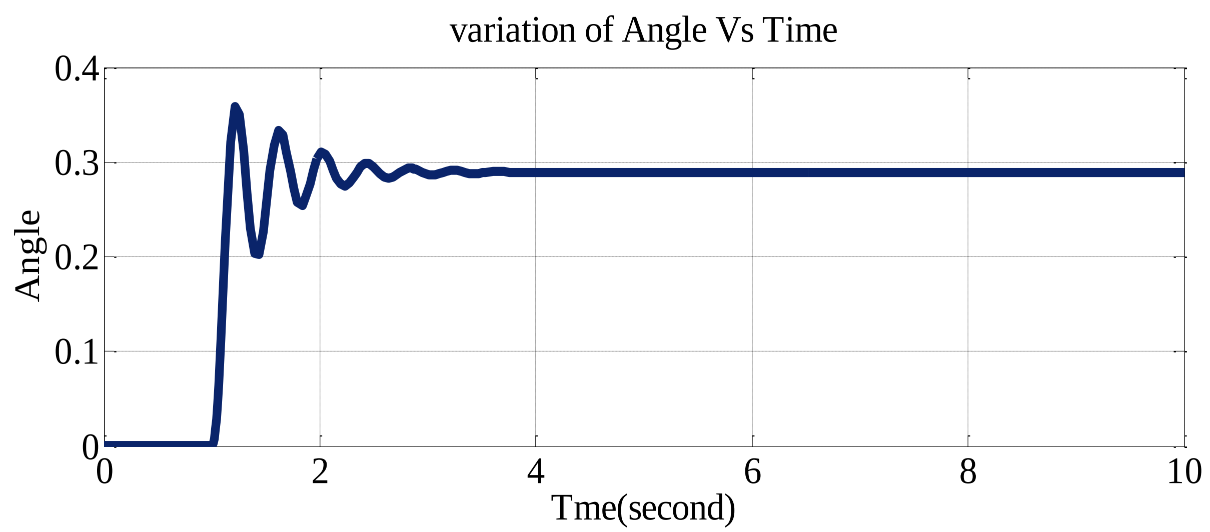


Fig. 2.18 Response of SMIB system with UPFC and Hybrid Fuzzy Logic Controller

- Comparison study of the impact of all controllers to the UPFC for controlling the effect of step changing on mechanical power input to the SMIB system is shown in the figure 2.19.

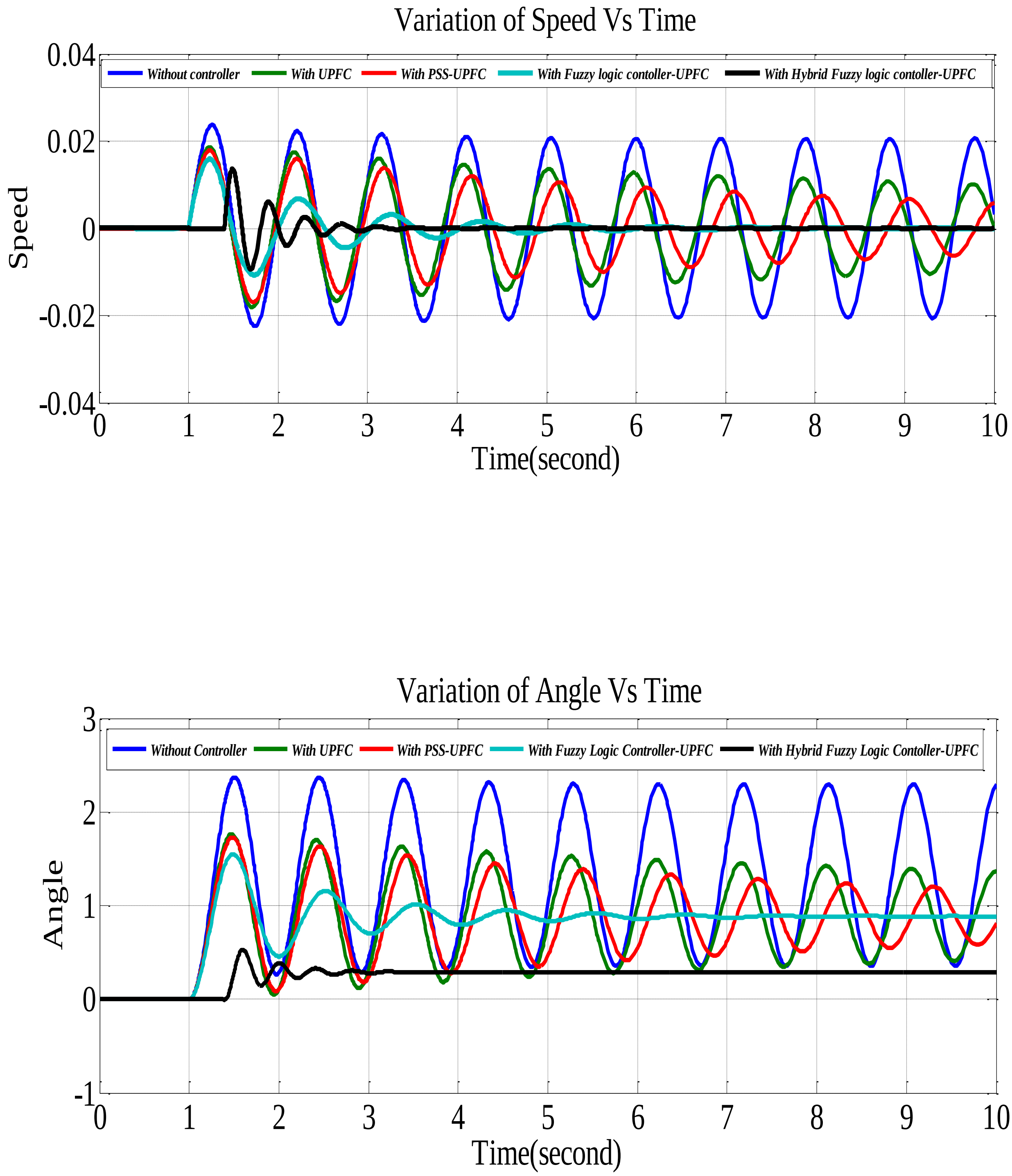


Fig. 2.19 Comparison of Response of SMIB system without and with UPFC with various controllers

Results Comparison:

CONTROLLERS	WITHOUT UPFC	WITH UPFC	UPFC WITH PSS	UPFC WITH CONVENTIONAL FUZZY LOGIC CONTROLLER	UPFC WITH HYBRID FUZZY LOGIC CONTROLLER
Settling Time(speed)	infinite	50 sec	15 sec	7.1 sec	3.3 sec
Settling Time(angle)	infinite	50 sec	15 sec	7.2 sec	3 sec

Table.1 Comparison of Response of SMIB system without and with UPFC with various controllers

DISCUSSION- From the above study with SMIB system connected to UPFC, PSS and also with FLC, simulation experiments and simulation results it is concluded that we can effectively damp out the low frequency oscillations by using Fuzzy and Hybrid Fuzzy logic controllers with only 7.2s and 3s, hence the stability of the system increases.

CHAPTER 3

POWER SYSTEM OSCILLATION DAMPING USING UPFC COORDINATED WITH POD AND PID CONTROLLERS.

CHAPTER 3

3.1 Introduction- The swift evolution of Power electronic sector gives an new idea and also empower the field of power system in many manner by developing new power electronics equipment's under the name of FACTS technology and is very much popular in last few decades. UPFC is used as most versatile and effective among all FACTS controllers for incising the stability of a system as well as control the power flow in the line [20]. This chapter also briefing the linear model of UPFC connected with the line and externally controlled by the signal from the proposed power flow controller to damp out the system oscillation with stability study with occurrence of fault. The proposed controller consist of Power oscillation damping controller and Proportional Integral Differential controller(POD & PID).The PID controller parameter has been optimized by Ziegler-Nichols tuning method. The simulation model is tested for both S-L-G and 3-ø faults. A power system is designed and examined by using phasor simulated process and the system is tested in three stages; without having UPFC, with UPFC but not having any external signal, power system having new proposed controller. It is seen that without the controller the all system parameters goes to unstable. When UPFC is connected in the system, it becomes stable. Again, when the UPFC is externally controlled by the proposed controller, the power system parameters (P, Q, and V) become stable very rapidly. It has been observed that UPFC rating is only 15 MVA with controller and 100 MVA without controllers. Therefore, UPFC is very effective to enhance the power system stability in good manner and also damp the power system oscillation.

3.2 CONTROL CONCEPT OF UPFC- The classical connection of UPFC with transmission line shown on the figure.3.1. The UPFC uses a two back-to back VSCs, operated from a common dc link. The converter 2 injects the controllable voltage both magnitude and phase angle to the connected line via series transformer. The converter 1 called STATCOM supplies or absorbed the real power demand by the converter 2 via dc link which then support the real power exchange between them. Conceptually the UPFC can automatically control all the system parameter that affect the power flow in a line, namely, voltage, impedance, and phase angle, hence, the name suggested "unified"[20]. The UPFC provides complete control over power flow in the line. A circuit equivalent diagram of the UPFC is show in the fig.3.2.

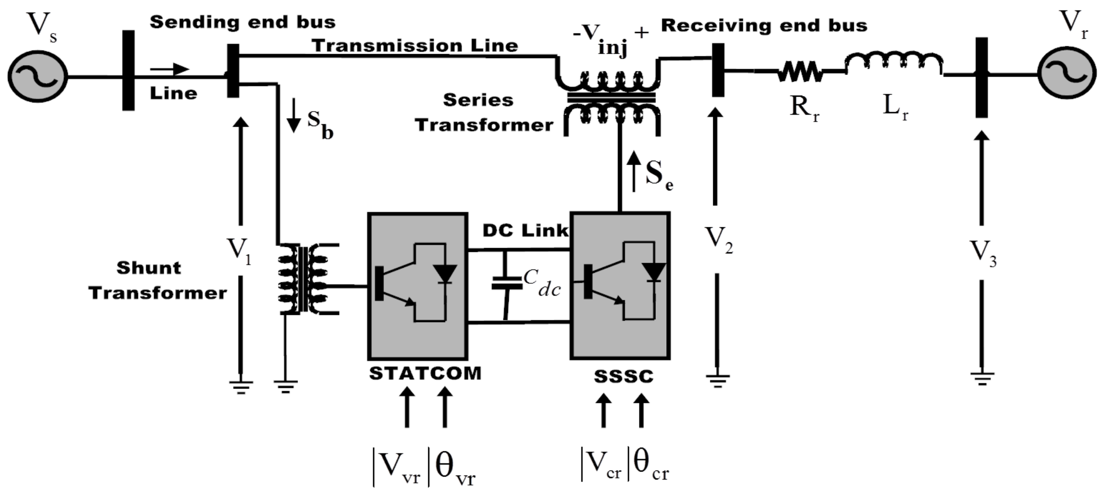


Fig.3.1. Connection diagram of UPFC with transmission line

3.3. UPFC BASED CONTROL SYSTEM- There is two modes of operation

1. PFC mode or automatic mode and
2. Manual voltage injection made

In the power control mode the comparison between the actual and reference values of the active and reactive power is made to produce an error P and Q. This error P and Q again synthesize by two voltage regulator and the VSC to compute the V_d and V_q. component (V_d and V_q are the direct and quadrature axis component with the voltage V_1 to control the power flow in the line). In manual voltage injection mode the use of voltage regulator is absent. The voltage of the converter is synthesized by the injected voltage V_{dref} and V_{qref} [20]. Fig.3.3 shows the block diagram of series converter

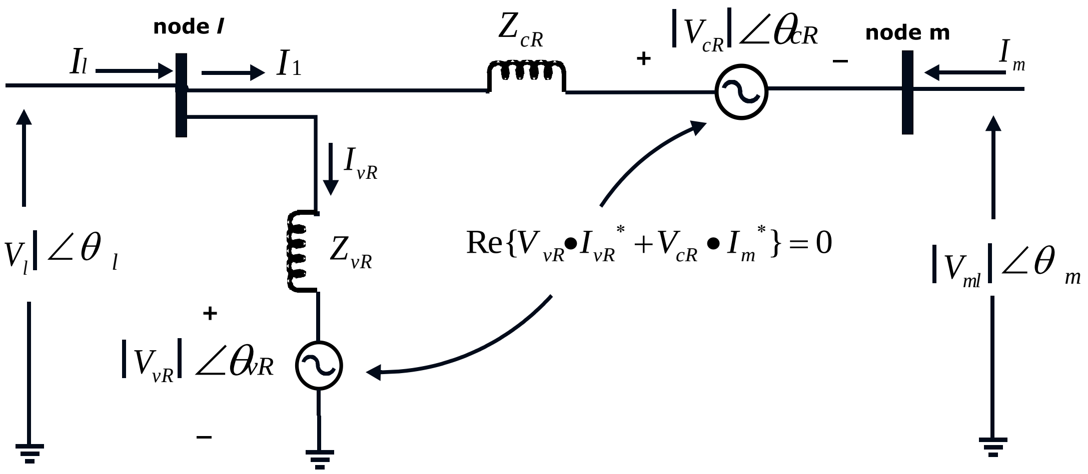


Fig.3.2. A general circuit equivalent of UPFC

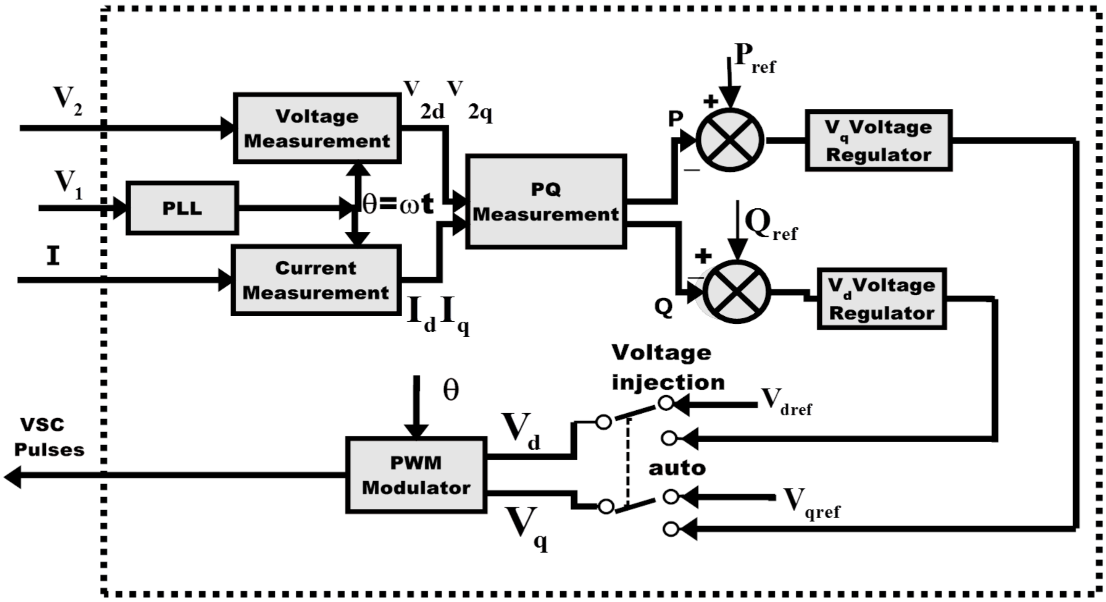


Fig.3.3. UPFC based control system

3.4. POWER SYSTEM MODEL WITH UPFC- Here model of a modest power system comprising of two-hydraulic power plants connected to a power grid is illustrated [21]. The whole Simulink model shown in figure.3.4. A UPFC is connected to regulate the power flow in a 500/230 kV transmission line. The power system used under the study is assembled in a loop arrangement, and it combination of five buses (B1, B2, B3, B4, B5).Three lines L1 to L3 are connected to make a ring system. Each plant having their own PSS, excitation system, speed regulators. The fig.3.4 shows the single line diagram of the two- machine system connected with UPFC. The UPFC is connected to the bus 3 via line 1-2 to control both the powers in the system also it control the voltage at the bus B_UPFC using two VSCs via dc link capacitor and the coupling reactors and the through transformers. The total generating capacity of 1500 MW and load connected are 1500 MVA, 500 KV, and 200 MW.

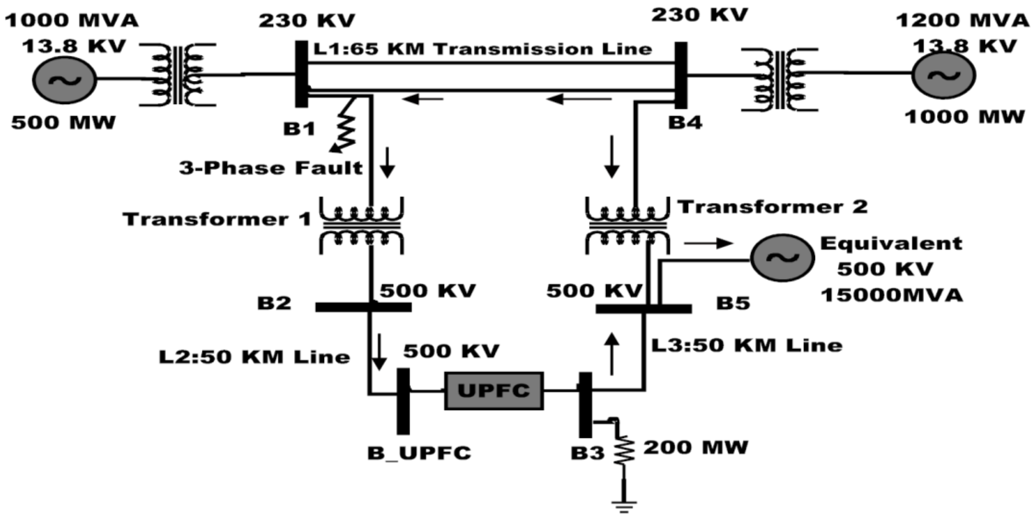


Fig.3.4 Single line diagram of two-machine power system with UPFC controller

3.5. DESIGN OF POWER FLOW CONTROLLER

The projected power flow controller consist of two different controllers, A. PID controller which is tuned by Ziegler-Nichols tuning method, B. POD controller.

3.5.1. PID Controller Tuning Process:

Input to the PID controller is the machine angular speed deviation and gives the output as an error signal. The PID tuning is done to selecting the proper controller parameter to meet the desire performance at particular condition. Most PID controllers are adjusted on-site, many types of tuning rules have been proposed in different literatures [22] [23]. The dynamic equation of PID control is given as:

$$u(t) = K_p e(t) + \frac{K_p}{\tau_i}\int e(t)dt + K_p \tau_d \frac{de(t)}{dt} \quad (41)$$

In Laplace Form,

$$\frac{U(s)}{E\ (s)} = K_P\left(1 + \frac{1}{\tau_i s} + \tau_d s\right) \quad (42)$$

Block diagram of PID controller Parameters is shown in the figure.3.5, for selecting the proper controller parameter, Ziegler-Nichols PID tuning method which is being used for the known system dynamics of the given plant is used. The parameter is selected as $\tau_i=\infty$, $\tau_d=0$.By means of the proportional controller action the K_p is increased from 0 to critical value K_{cr} which is shown in figure.3.6., Fig.3.7 shows the output of the sustained oscillation.

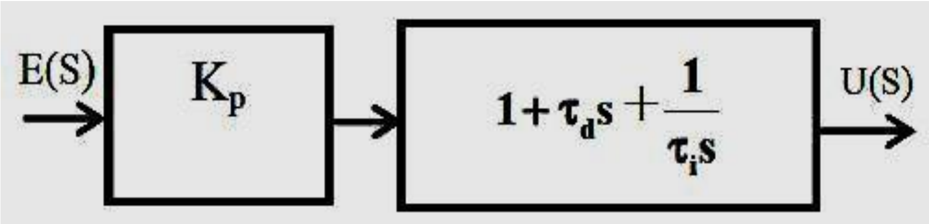


Fig.3.5 Block diagram of PID controller Parameters

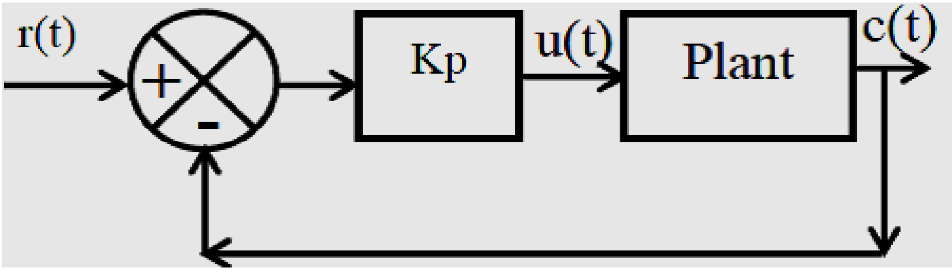


Fig.3.6 Proportional action of PID controller

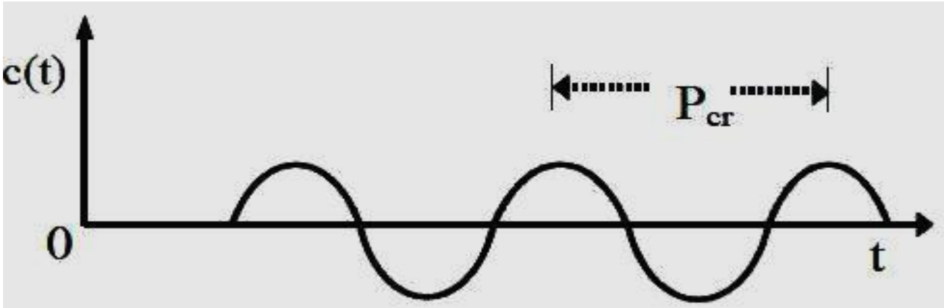


Fig.3.7 Calculation of sustained oscillation (P_{cr})

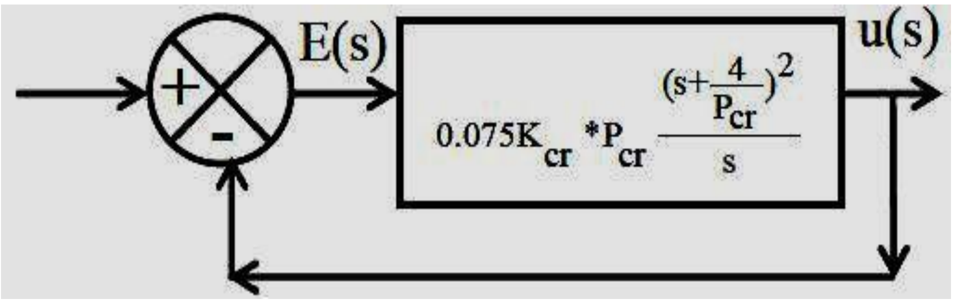


Fig.3.8 PID controller with tuning parameters

Thus experimentally the critical gain K_{cr} & its corresponding critical time period P_{cr} are determined. Then according to Ziegler and Nichols the value of the parameter Kp, τ_i, τ_d must set according to the subsequent formula.

$$K_p=0.6K_{cr},\ \tau_i=0.5P_{cr},\ \tau_d=0.125P_{cr}$$

Using this tuning method for PID controller, the result which is obtained is given by,

$$G_c(s) = K_p\left(1+\frac{1}{\tau_i s}+\tau_d s\right) \quad (43)$$

$$G_c(s) = 0.6K_p(1+\frac{1}{0.5P_{cr}s}+0.125P_{cr}s) \quad (44)$$

$$G_c(s) = 0.075K_{cr}\times P_{cr}\frac{(s+\frac{4}{P_{cr}})^2}{s} \quad (45)$$

Thus the PID controller has a pole at origin and two zeros at S= -4/P_{cr}. It is found that, P_{cr} =0.2s & K_{cr} =200 from figure 3.5. Block diagram of PID controller with tuning parameter shown in the figure.3.8. By taking the input as machines angular speed deviation dω1 and dω2 it generates an output error signal dω, which is shown in the figure.3.9.

3.5.2. Design of POD controller

The inputs to the POD controller are V_{abc} , I_{abc} & convert it as power. At normal condition the controller switch are open and it follows the system to close the switch when the fault occurs to produce an error signal [24][25]. The internal structure of POD controller is shown in the figure.3.10.

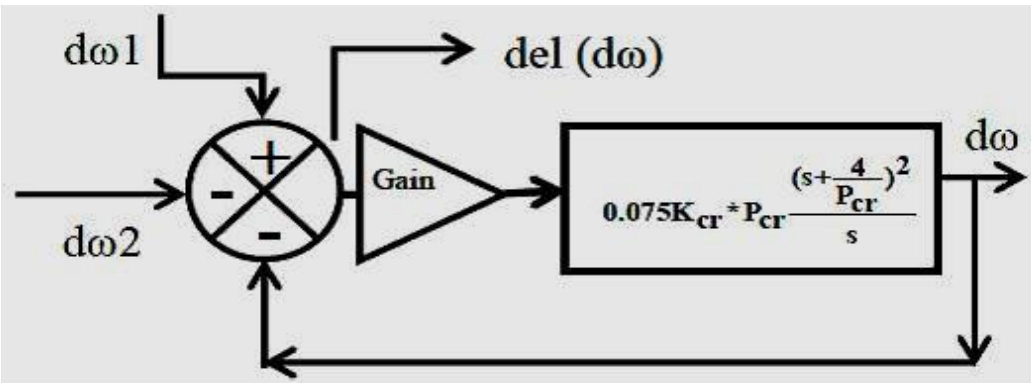


Fig.3.9 Internal structure of PID controller with dω1& dω2 input

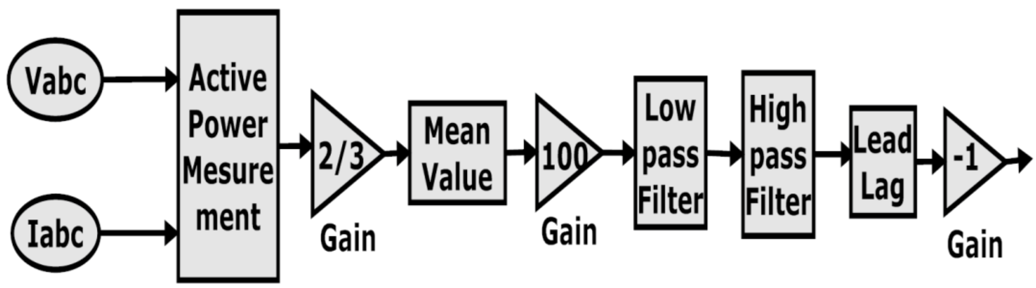


Fig.3.10 Internal structure of POD controller

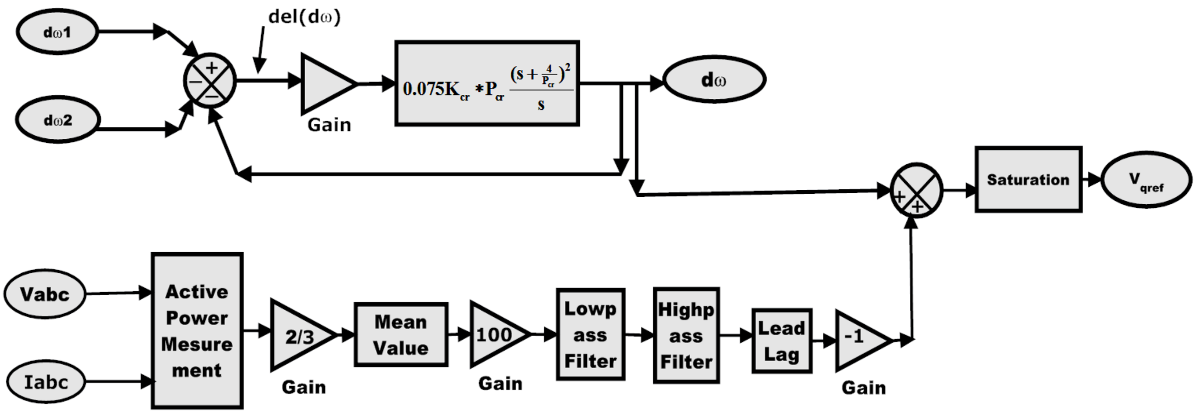


Fig.3.11 Complete model of Power Flow Controller

Finally two error signals one from PID and other from POD has been added to form Power System Controller to give the reference voltage signal V_{qref}. This output is used as a reference signal and again given to the UPFC when it operates in manual voltage injection mode for improving the stability and damp out the oscillation. The complete internal structure of power system controller is shown in the figure.3.11.

3.6 Simulation Results and Discussion

The simulation is carried out for two different types of fault condition.

Case A. S-L-G fault

Case B. 3-Ø fault

Case A.1: S-L-G fault (without UPFC)When S-L-G fault happened at 0.1s and the fault breaker unlocked at 0.2s (3-phase 4-cycle fault), as there is no UPFC connected the whole system voltage and power turn out to be unstable. The responses of the system are shown in fig.3.12 andfig3.13.

CaseA.2: S-L-G fault (UPFC without power flow controller)

If UPFC is connected, the responses of the system are shown in fig.3.14 and fig.3.15.

Case B.1: 3-ø (without UPFC)

Throughout 3-Phase faults, if UPFC is not connected, then again system voltage and power going to be unstable. The simulation results are shown in figure.3.16 and figure.3.17.

Case B.2: 3-ø fault (UPFC without power flow controller)

During Three-Phase faults, If UPFC is connected to the system, the simulation results are shown in the figure.3.18 and figure.3.19.

Case A.3: S-L-G fault (UPFC with power flow controller)

If UPFC with PFC is connected to the system, the simulation results are shown in fig.3.20 and fig.3.21.

Case B.3: 3-ø fault (UPFC with power flow controller)

During Three-Phase faults, If UPFC is connected to the system, the simulation results are shown in the figure.3.22 and figure.3.23.

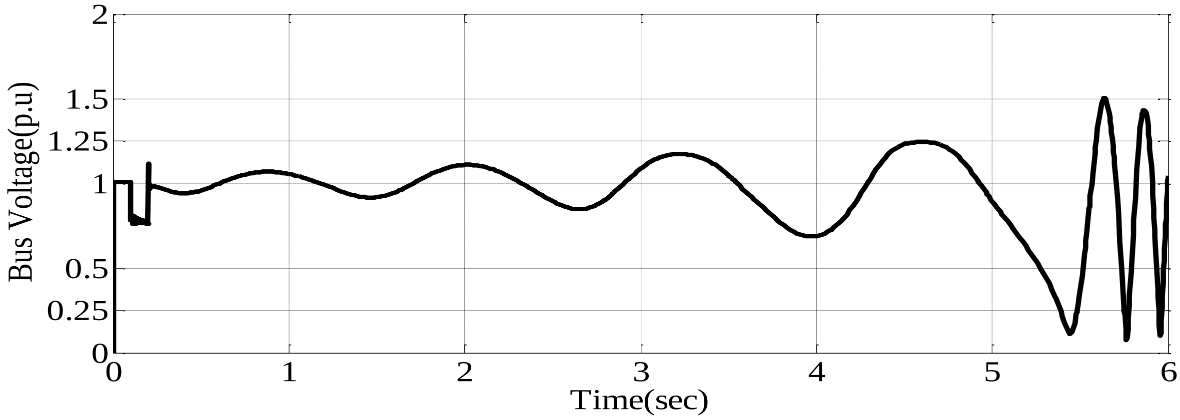


Fig.3.12 Bus voltage (B1) in p.u. without UPFC

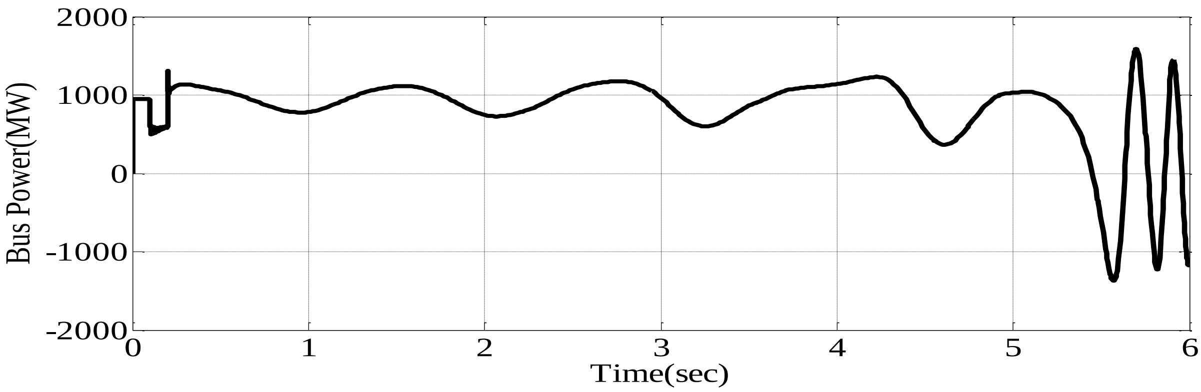


Fig.3.13 Bus power (B1) in MW without UPFC

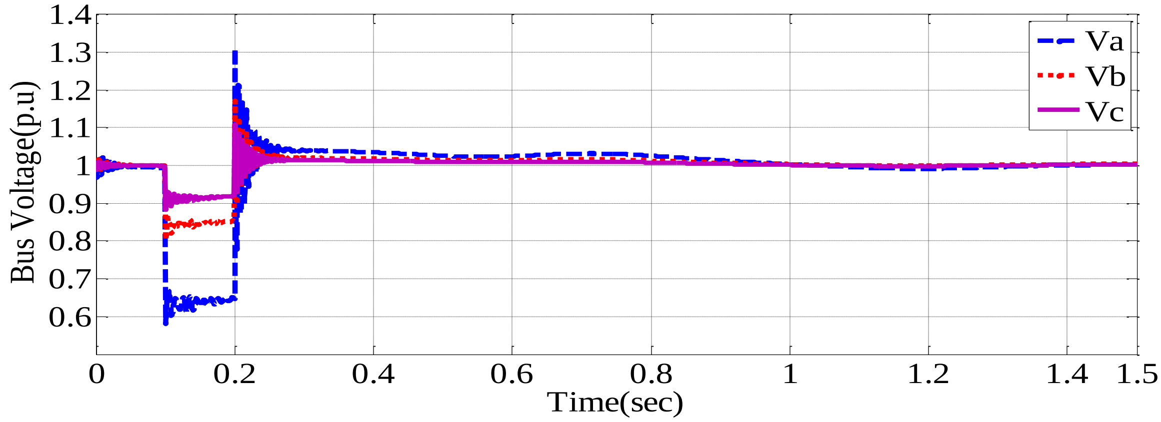


Fig.3.14 Bus voltage in p.u. (UPFC without power flow controller)

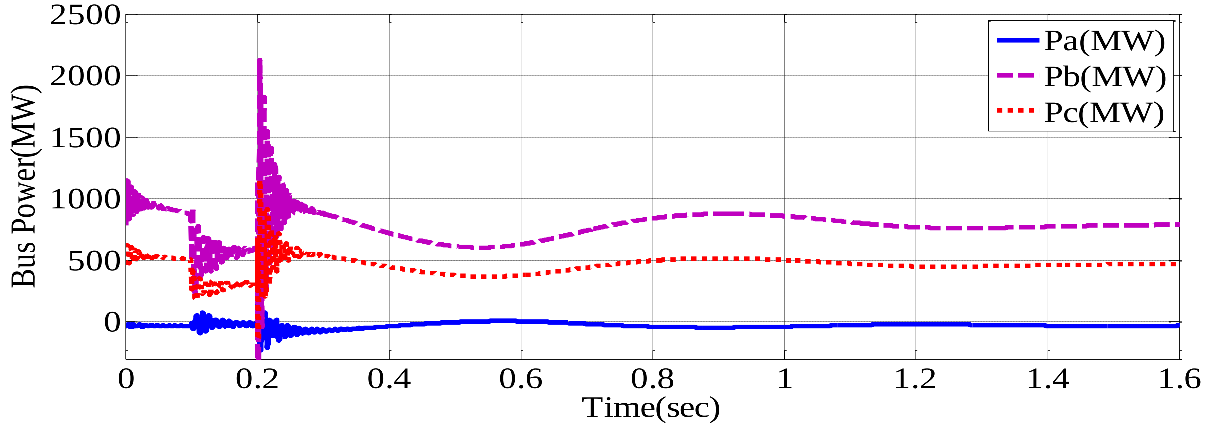


Fig.3.15 Bus power in MW (UPFC without power flow controller)

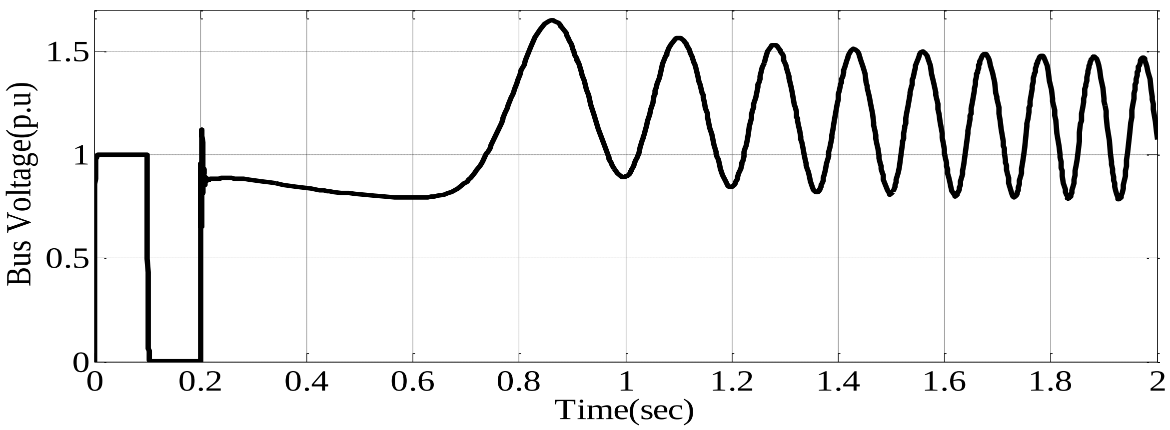


Fig.3.16 Bus voltage (B1) in p.u. without UPFC

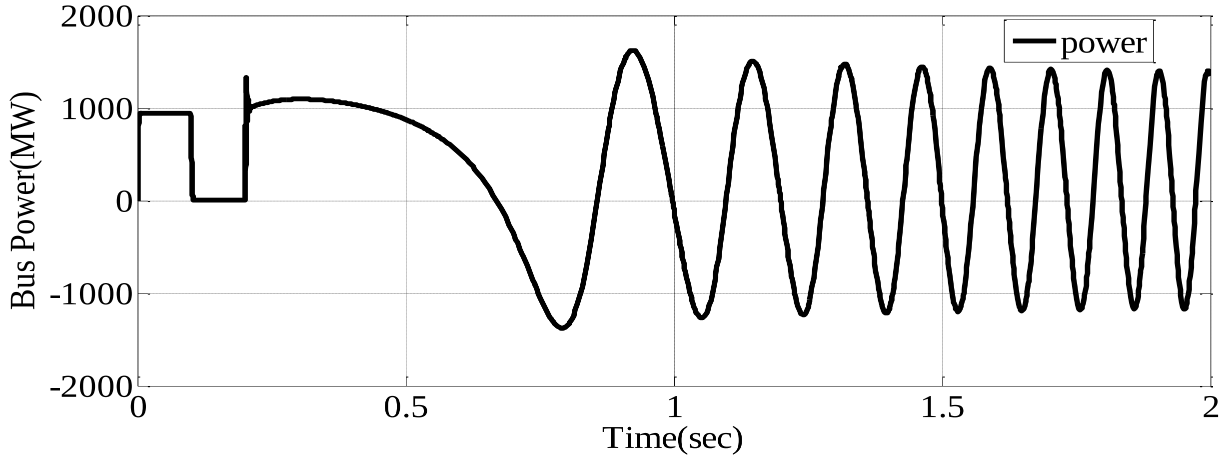


Fig.3.17 Bus power (B1) in MW without UPFC

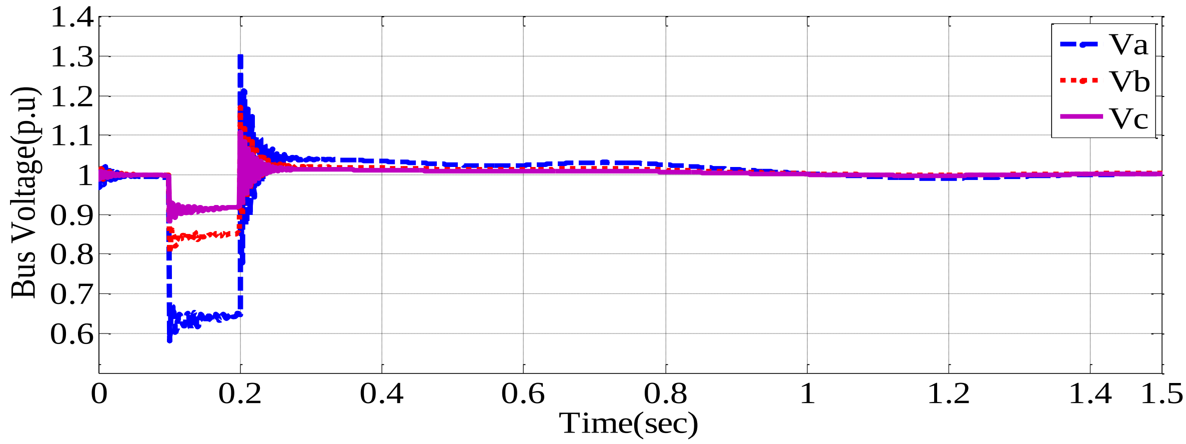


Fig.3.18 Bus voltage in p.u. (UPFC without power flow controller)

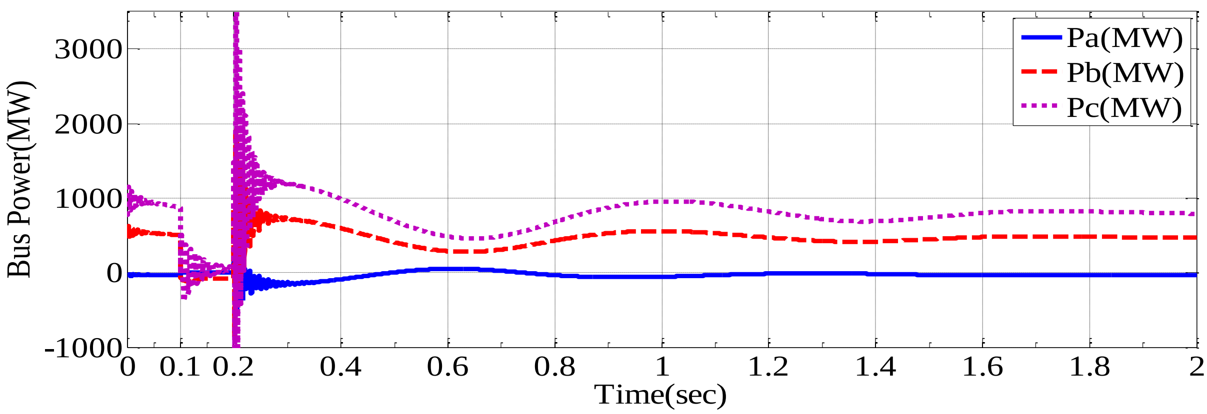


Fig.3.19 Bus power in MW (UPFC without power flow controller)

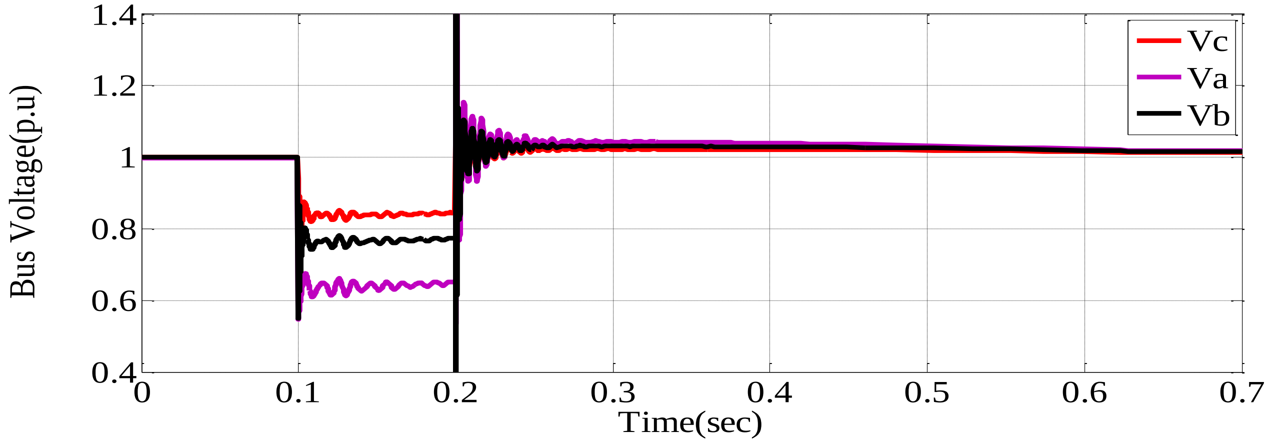


Fig.3.20 Bus voltage in p.u. (UPFC with power system controller)

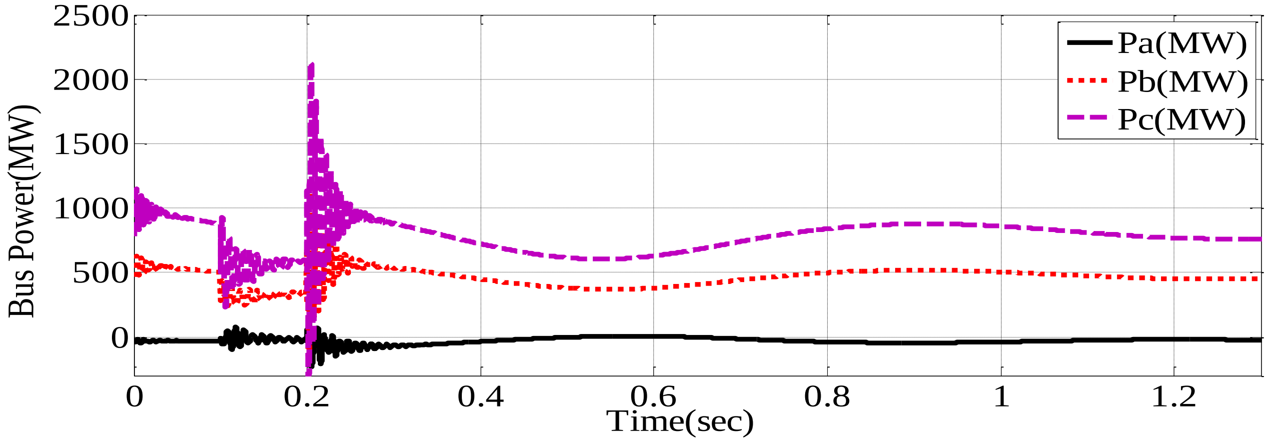


Fig.3.21 Bus power in MW (UPFC with power system controller)

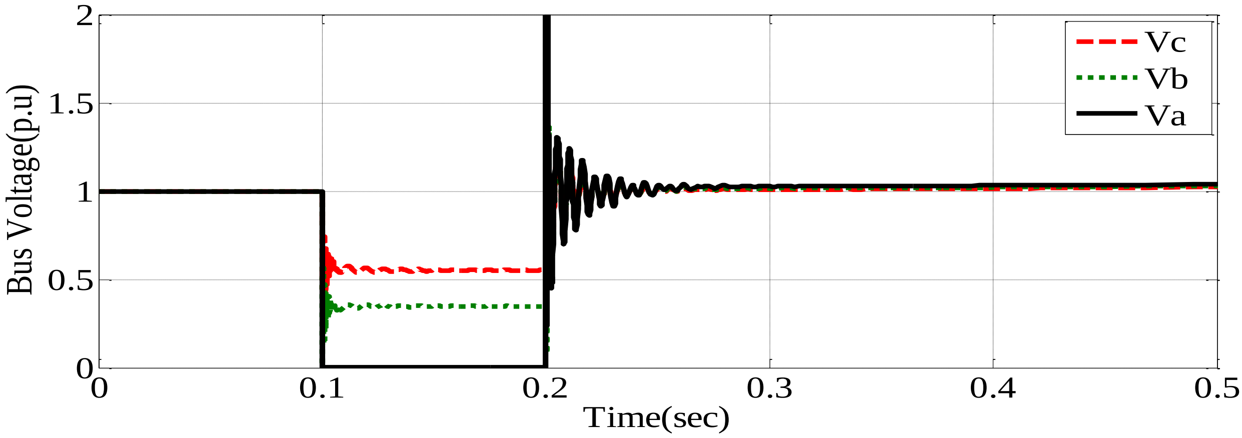


Fig.3.22 Bus voltage in p.u. (UPFC with power flow controller)

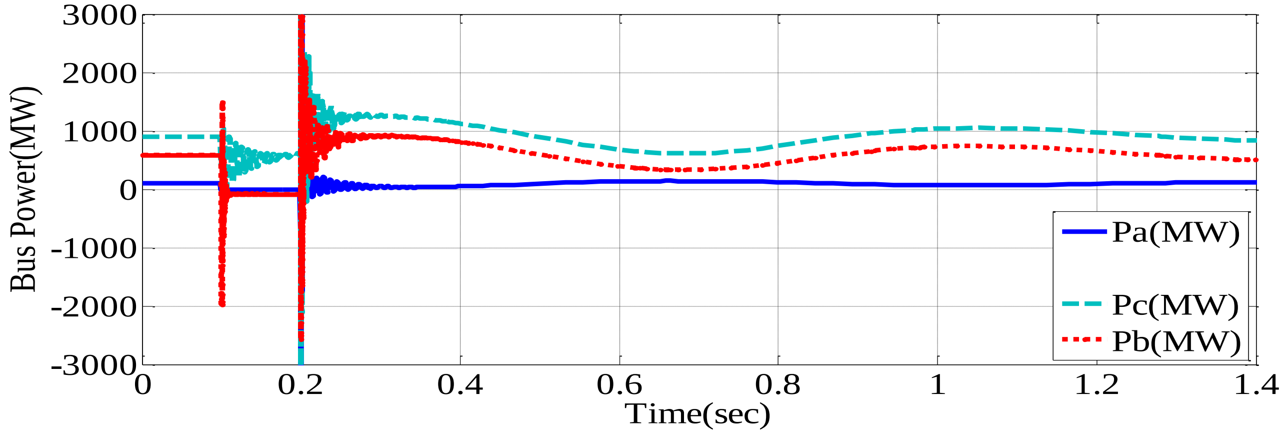


Fig.3.23 Bus power in MW (UPFC with power flow controller)

- The performance of UPFC with Power Flow Controller having same 500KV transmission line is summarized in table 1. Below.

		SETTLING TIME			
		1-Phase Fault		3-Phase Fault	
Status	UPFC	Voltage	Active Power	Voltage	Active Power
No UPFC	NO	∞	∞	∞	∞
UPFC	100MVA	1.5s	1.6s	1.5s	2.1s
UPFC+PFC	15MVA	0.6s	1.25s	0.3s	1.4s

Table.2 The performance of UPFC with PFC having same 500KV transmission line

DISCUSSION: - The above simulation results gives an idea about that UPFC not only significantly increases transient stability limits but also compensates the power system oscillations during both single phase and three phase faults. The UPFC with power flow controller very much effective to control the both active and reactive power flow of power system by injecting suitable reactive power during fault condition and damp the oscillation for active power in just 1.25s for single phase and 1.4s for three phase faults and for voltage it is 0.6s single phase and 0.3s for three phase.. We also conclude that if the fault clearing time is less, more stability improvement. On the other hand less transient stability improvement occurs if fault clearing time is more.

CHAPTER 4

CONCLUSION AND FUTURE SCOPE

CHAPTER 4

4.1 CONCLUSION-In the chapter 2, a brief discussion is made about the LFO and small signal stability of a system. A linearize Haffron-Philips model is considered and a dynamic behavior of the system was examined by using different controllers like UPFC with power system stabilizer, conventional Fuzzy logic controller, Hybrid fuzzy logic controller..etc. to the small change in excitation and mechanical input. From the figure it is observed, that the planned Hybrid fuzzy logic UPFC controllers significantly damp power system oscillations effectively compared to the conventional Fuzzy logic UPFC. In chapter 3, the whole system presents the effectiveness and stability response of the UPFC without and with power flow controller on the dynamic behavior of the power system with external fault, real & reactive power flow, voltage level for different type of fault (single and three phase faults) conditions. If Power Flow Controller is connected then lesser rating of UPFC becomes sufficient for stabilization of the system oscillation at very shortest interval of time for both the steady and dynamic conditions.. This power flow controller can use with any FACTS devices for any type of system like single or multi machine system to enhance the stability of the system with damping the oscillation .

4.2 FUTURE SCOPE- These proposed controller can applied to any other FACTS devices with tuning algorithm i.e. ANN, Fuzzy logic, Genetic algorithm. In future a Fuzzy logic based POD controller will be designed to control the UPFC for power system oscillations. We can also enhance our projects from SMIB system to multi machine system for small signal analysis.

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PUBLICATION

[1] Sudhansu Kumar Samal, P.C.Panda, "Damping of Power System Oscillations by Using Unified Power Flow Controller with POD and PID Controllers", IEEE Conference (ICCPCT), 2014, .978-1-4799-2395-3/14/$31.00 ©2014 IEEE.